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Integrated Life Cycle Design - Applied to concrete multi-dwelling buildings

Öberg, Mats

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LUND UNIVERSITY

PO Box 117
221 00 Lund
+46 46-222 00 00

LUND INSTITUTE OF TECHNOLOGY
LUND UNIVERSITY

Division of Building Materials

INTEGRATED LIFE CYCLE DESIGN

Applied to Swedish concrete multi-dwelling buildings

Mats Öberg

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Cover: Contemporary Swedish concrete multi-dwelling building
in Hässelby, Stockholm
Architect: Anders Bergkrantz Arkitektkontor
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Lund Institute of Technology
Division of Building Materials
Box 118
SE-221 00 Lund, Sweden

Telephone: 46-46-2227415
Telefax: 46-46-2224427
www.byggnadsmaterial.lth.se

ABSTRACT

The objective of this work is to explore ways of enhancing the overall lifetime quality, including cost and environmental efficiency, of Swedish concrete multi-dwelling buildings. The building and its characteristics, as well as the procedures for whole life optimisation, are addressed. The methods developed are general for buildings, while the application is specific.

The fundamental characteristics (attributes) of dwelling buildings are reviewed, and a set of design criteria relating to these is compiled. Furthermore, the properties of concrete with regard to the attributes are analysed.

The concept of Integrated Life Cycle Design is applied as methodological platform. By integrated life cycle design the traditional design procedure, is supplemented by life cycle appraisal and methods to optimise the building with regard to several more or less interacting parameters.

A pilot toolbox for integrated life cycle design of residential buildings is developed and verified. This contains a set of design criteria addressing the fundamental attributes, modules for life cycle costing, energy balance calculation, structural and acoustic pre-design, environmental assessment and feed-back routines. The environmental assessment is based on a socio-economic cost estimation, relating to energy consumption during the user phase. Energy use for production and demolition are also taken into account, but only as average values. For the concrete building frame, a full LCA model, regarding the production phase is also developed. For the ranking of technical alternatives, in relation to the priorities of the client, 'Multiple Attribute Decision Analysis', 'MADA', was also included in the study and in the toolbox.

The Integrated Life Cycle Design toolbox is tested and further developed by the application on eight real cases. A comparative desktop study on the resulting lifecycle consequences, from different functional quality levels is also undertaken.

It was concluded that integrated life cycle design may enhance the lifetime quality and cost effectiveness of buildings and thus deserves introduction in practice. The life cycle appraisal tools and data are available and calculations can be done with reasonable effort, giving reliable results. The application examples show how integrated life cycle design can guide design decisions towards the optimal building with regard to specific priorities of the client.

Key words: Energy efficient buildings, Integrated life cycle design, Life Cycle Costing, Life Cycle Assessment, Multiple Attribute Decision Analysis, Service life design, Sustainable construction.

PREFACE

In Sweden, as in many other countries, concrete is the most frequently used structural material for multi-dwelling buildings. It was conceived that the structural as well as a number of other potentially favourable properties of concrete were not fully utilised in the current design practice. This idea transformed into the research objective of how to optimise a building over its lifecycle. Concrete multi-dwelling buildings were consequently selected as the application example, but the methods and criteria are generic why the work should be of interest in a general building design context.

The research objective covers two main areas: One is the analysis and systemization of the important requirements on a residential building over the life cycle. The second is the review and compilation of design methods that facilitate lifetime quality optimisation. It is acknowledged that both these areas are broad as well as complex enough to sustain endless specific research efforts. The ambition of this work is to align current theory with practice, and to establish criteria and methods that can be applied in the real design situation.

The supervisor for this work has been Professor Emeritus Göran Fagerlund, whom I would like to thank for his endless inspiration and commitment. Furthermore I would like to express my gratitude to:

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CONTENTS

SUMMARY

Buildings represent large and long-lasting investments in terms of economy as well as other resources. We spend a large part of our lives in buildings and the indoor environment affects our well-being and health. Improved lifetime quality and cost effectiveness of buildings are therefore of common interest for owners, users as well as the society and, consequently, plays a key role in sustainable development.

Background and aim (Chapter 1)

Design and procurement based on whole life appraisal can improve functional quality and, therefore, the overall cost and environmental effectiveness of buildings. Empirical studies and examples from other sectors support this claim, yet a small proportion of house building projects adopt life cycle design principles. In this regard, whole life appraisal is examined by considering both design procedures and the functional characteristics of the building.

The aim of this work is to explore and indicate ways of designing a building to achieve the optimal overall lifetime performance. The selected approach is to adopt the state-of-art theory and findings from available application examples, into a methodology, that can be directly used and further developed in practical design of buildings. Simplicity in use, availability of input data, adaptability and transparency are therefore prioritised.

The primary contribution of the work is to advance the use of holistic life cycle design in the building design practice.

The Swedish concrete multi-dwelling building is the application example but the methodology is open and general. The fundamental lifetime quality factors for buildings are addressed, but the focus is placed on the influence of, and potential contributions from, the building frame.

State of the art of holistic lifetime optimisation of buildings (Chapter 2)

The theoretical background to holistic lifetime optimisation is clearly outlined and systemised by professor Asko Sarja, within the framework of 'Integrated Life-time Engineering', where 'Integrated Life Cycle Design', 'ILCD', is one part.

The application models for holistic lifetime optimisation that have been presented, such as the GBTool or the CASBEE model are typically very comprehensive and sophisticated in their organisation. However, the link to the required quantitative calculation methods as well as data to put into the models, require further development.

Although, life cycle costing has been applied in other sectors since decades and relevant input data is available from facility management, it is not commonly used by design of residential buildings.

For environmental assessment a method (LCA) is available, but there is still some work needed to obtain general agreement with regard to the valuation of different environmental stressors. For the specific application of comparing entire design alternatives of buildings there is, furthermore, a lack of reliable quantitative environmental data on building products and materials.

This means that in the real design situation, the threshold for the introduction of holistic life cycle design, and related methods, in the house-building sector is high.

Interpretation of the problem and outline of research questions (Chapter 3)

Integrated Life Cycle Design was applied as methodological platform, for the development of a toolbox for simplified whole life optimisation of residential buildings. The methodology described in previous work was analysed and interpreted. ILCD is a combination of two principles:

- Integration, which implies that components and systems should be designed with understanding and respect of their interaction with other systems and the building as a whole.
- Life cycle, meaning that the design should take costs and environmental burdens of production, use and final disposal into consideration.

The following major research questions are defined:

- To map the fundamental lifetime quality characteristics (attributes) for Swedish multi-dwelling buildings.
- To establish relevant ILCD criteria for the attributes.
- To define different functional quality levels for the attributes.
- To study how modular life cycle planning can be applied to decompose the building into logical units for service life design, to aid the design and selection of systems and materials.
- To compile a toolbox for simplified ILCD that fits into the current design practice.
- To examine the economical and environmental life cycle consequences of alternative levels of functional quality.

The fundamental attributes of buildings (Chapter 4)

A building must by its characteristics, here referred to as attributes, respond to a number of different requirements. The following fundamental attributes are identified selected and analysed. Also the properties of concrete in relation to the attributes are examined.

Essential requirements of the CPD[1]:	Other:
Mechanical resistance and stability	Robustness
Safety in case of fire	Lifetime usability
Hygiene, health - indoor environment	Architecture
Safety in use	Life cycle costs
Protection against noise	Lifetime environmental burden
Energy economy and heat retention	

Durability

A generic set of design criteria relating to the attributes is envisaged and to this a classification organised in three quality levels is proposed. Some of the attributes are easy to characterize and quantify, while others must be treated qualitatively.

The toolbox for simplified integrated life cycle design (Chapter 5)

A toolbox for simplified ILCD has been developed featuring the following main functions:

I. Analysis of client needs. Design criteria and classification relating to the attributes are established.

II. Life cycle appraisal. Economical and environmental life cycle appraisal to quantify life cycle consequences of alternative designs. Modular lifetime planning is outlined.

III. Ranking methods. Multiple Attribute Decision Analyses is employed to aid the choice of design with regard to several different aspects.

IV. Feed back. Principles and methods for feedback of information from production and facilities management of the building is outlined.

As mentioned above a key feature was simplicity and concentration on the most decisive lifetime quality factors. The toolbox can be applied with increasing level of detail following the design process from early sketches to tender and construction documentation.

Application of ILCD toolbox. Theoretical and real projects (Chapter 6-7)

In a desk-top study on a theoretical building the main steps and features of the ILCD-process and the toolbox are presented. The example is also utilised to map the lifetime consequences with regard to economy and environmental burden dependent of the functional quality level applied. The conclusion was that in this example a higher functional quality level was not in conflict with low cost and environmental burden.

The pilot ILCD toolbox was tested and improved by performing various tasks in eight real projects, from early planning phases to follow up.

[1] '*Directive on construction products'* Directive 89/106/EEC of the EU

Introduction of ILCD in practise, discussion and future work (Chapter 8-9)

The toolbox is ready to use in real projects, in its present state, or to be further developed and customised. Life cycle costing and environmental assessment can be undertaken with optional level of detail. The method for multiple-attribute decision analysis is a good way to systemise the requirements, while the final weighting step is sensitive and further experience of the method is required. As in the desktop example, the life cycle cost comparison indicated relatively small differences between design alternatives, thus their functional quality can govern the design choices. This is an important conclusion, which should favour the better performance alternatives.

Views on the methodology, by people in the project teams, are mapped. The response is in principle positive, although, several problems were identified. Some problems are, however, more related to the organisation of the building process, than to the ILCD concept.

The practical introduction of ILCD in the building design process is discussed. Data requirements are listed. Ideas on immediate improvement of the ILCD toolbox, as well as its position in a future, product model based design process, including the time dimension, are outlined.

Findings with regard to building technology were that buildings should be adaptable over time to avoid waste of resources by obsolescence. Ambient climatic conditions also require adaptability, regarding design for energy efficiency, indoor climate and building physics in general. According to analysis of attributes and functional properties, the contribution of concrete to sustainable multi-dwelling buildings is to provide robustness, load carrying capacity and shielding functions. This is in the modular lifetime planning defined as the 'primary structure'.

Production, periodic maintenance and the heating cost have the most significant influence on the life cycle cost. From the environmental load point of view heating dominates. These items are all to a large extent dependent on the design of the building.

The work confirms that ILCD can contribute to improved lifetime quality and cost and environmental efficiency of residential buildings. With ILCD:

- The functional quality aspects of the building can be systematically addressed, in a holistic way.
- The life cycle cost and environmental burden with regard to the alternative lifetime quality levels, or designs, can be quantified.

SAMMANFATTNING. (SUMMARY IN SWEDISH)

Byggnader utgör en stor och långvarig investering, såväl beträffande ekonomi, som andra resurser. Människan tillbringar en stor del av sitt liv inomhus och inomhusmiljö påverkar välbefinnande och hälsa. Att förbättra byggnaders funktion och kostnadseffektivitet är därför av gemensamt intresse för förvaltaren, de boende och samhället. Byggnaden spelar en nyckelroll i hållbar samhällsutveckling.

Bakgrund och syfte (Kapitel 1)

Projektering och upphandling baserat på helhetssyn och livscykelperspektiv kan öka funktionell kvalitet, kostnadseffektivitet och miljöprestanda. Trots att studier och exempel från andra sektorer stöder denna tes, tillämpas den sällan inom bostadsbyggandet. I detta arbete studeras helhetsprojektering av bostadshus såväl i fråga om metodik, som byggnadens egenskaper och funktion.

Syftet med arbetet är att undersöka och påvisa hur ett hus kan projekteras så att funktionen på bästa sätt motsvarar de krav som ställs, till lägsta möjliga kostnad och miljöpåverkan över hela livscykeln. Angreppssättet är att utifrån tillgänglig teori och exempel, utveckla en metodik som kan användas praktiskt, och också vidareutvecklas, för projektering av bostadshus. Enkelhet, anpassningsbarhet, transparens och tillgång till data prioriteras därför.

Arbetets primära bidrag är att driva på introduktionen av projektering med helhetssyn och livscykelperspektiv inom husbyggande.

Svenska flerbostadshus med stomme av betong utgör tillämpningsexempel men metoden är öppen och generell. Arbetet innefattar alla viktiga funktionskrav för byggnader, dock är fokus riktat mot stommens påverkan och möjliga bidrag till god funktion.

Nulägesanalys av området helhetsprojektering av byggnader (Kap. 2)

Teoretisk bakgrund till helhetsoptimering av byggnader har utvecklats och systematiserats av professor Asko Sarja inom ramverket ‘Integrated life-time Engineering’, där integrerad livscykelprojektering, ‘Integrated Life Cycle Design’, ’ILCD’, ingår som en del.

De tillämpningar av ILCD som har utvecklats, t.ex. GBTool eller CASBEE är mycket omfattande och detaljerade i sin struktur. De är dock i första hand inriktade på administration av projekteringsprocessen och saknar ofta koppling eller tillgång till de kvantitativa verktyg och data som krävs för praktisk användandning vid vanlig husprojektering.

Trots att livscykelkostnadsberäkningar sedan länge använts som beslutsstöd inom andra sektorer, och att nödvändiga data finns att tillgå, så används metodiken sällan vid projektering av flerbostadshus.

LCA kan användas för värdering av miljöbelastning, men när det gäller värderingen av olika miljöpåverkande faktorer pågår fortfarande arbete för att nå full konsensus. För att kunna jämföra miljöbelastning av olika konstruktionsalternativ för hela byggnader saknas också kvantitativa miljödata för byggprodukter och material. Vissa förenklade värderingsmetoder beskrivs i litteraturen.

Sammantaget innebär detta att tröskeln till införandet av integrerad livscykelprojektering för hus, är hög.

Tolkning av problemställning och formulering av forskningsfrågor (Kap. 3)

Integrerad livscykelprojektering, 'ILCD', valdes som bas för utveckling av en verktygslåda för förenklad helhetsprojektering av bostadshus. Metoder som beskrivs i tidigare arbeten analyseras och tolkas. ILCD är en kombination av två principer:

- Integrering, innebärande att komponenter och system projekteras med insikt och respekt för deras funktion i samspel med övriga delar och helhet.
- Livscykel, varvid kostnader och miljöbelastning för produktion, användning och rivning tas i beaktande vid val av konstruktioner.

Följande primära forskningsfrågor definierades:

- Att analysera väsentliga egenskaper (attribut) för flerbostadshus.
- Att definiera ILCD – kriterier för attributen.
- Att ta fram ett antal funktionella kvalitetsnivåer för attributen.
- Att studera hur byggnadens delar och system kan ordnas i logiska moduler för livstidsplanering för att stödja konstruktion och val av material och system.
- Att utveckla en verktygslåda för förenklad ILCD som passar in i dagens sätt att projektera hus.
- Att undersöka ekonomiska konsekvenser av val av olika kvalitetsnivåer i fråga om funktionell kvalitet.

Byggnadens väsentliga egenskaper, 'attribut' (Kapitel 4)

En byggnad måste genom sina egenskaper svara upp mot en rad olika krav. Vissa krav är samstämmiga medan andra kan stå i konflikt med varandra. Nedanstående egenskaper behandlas i detta arbete. Materialet betongs egenskaper i förhållande till attributen värderas också.

Väsentliga egenskaper enligt BPD[2]:	Andra:
Bärförmåga och stabilitet	Robusthet
Brandsäkerhet	Användbarhet över livscykeln
Inomhusmiljö	Arkitektur
Säkerhet vid användning	Livscykelkostnad
Ljudmiljö	Belastning på den yttre miljön
Energihushållning	

Beständighet

En uppsättning allmänna kriterier för projektering relaterade till attributen utvecklas och till dessa en klassificering i tre alternativa kvalitetsnivåer. Vissa attribut är enkla att karakterisera och kvantifiera medan andra måste behandlas kvalitativt.

Verktygslådan för integrerad livscykelprojektering (Kapitel 5)

En verktygslåda för förenklad ILCD har utvecklats som innehåller följande huvuddelar:

I. Analys av krav på byggnaden. Funktionsinriktade kvalitetskriterier med tillhörande klassificering i tre nivåer, från minimistandard enligt norm till bästa nuvarande praxis.
II. Livscykelvärdering, omfattande ekonomi och miljöbelastning för att kvantifiera konsekvenser av konstruktiva val över hela livscykeln. Modulär livslängdsplanering behandlas.
III. Metod för rangordning av alternativ med hänsyn till många olika krav relaterade till kundanalys och aktuell prioritering.
IV. Erfarenhetsåterföring. Principer och metoder för systematisk återföring av information från produktion och drift till projekterande led.

Som nämnts ovan har enkelhet vid användning prioriterats och fokus har lagts vid de mest avgörande kvalitetsegenskaperna under livscykeln. I likhet med hur projekteringsprocessen, från tidigt program till bygghandlingar och anbudsvärdering fungerar, kan verktygslådan användas med stigande detaljnivå.

Tillämpning av verktygslådan. Teoretiskt och i projekt (kapitel 6-7)

I en studie av ett teoretiskt hus presenteras stegen och procedurerna som ingår i ILCD och verktygslådan. Exemplet används också för att undersöka ekonomiska och miljömässiga konsekvenser av att välja olika funktionella kvalitetsnivåer. Slutsatsen i detta fall var att högre funktionell kvalitet ej stod i konflikt med god ekonomi och låg miljöbelastning.

[2] '*Direktiv om byggprodukter'*. Direktiv 89/106/EEC av Europeiska unionen

Verktygslådan prövades och vidareutvecklades genom att utföra olika typer av uppgifter, från tidiga skeden till uppföljning, vid åtta olika verkliga projekt.

Metoden för helhetsoptimering är en bra grund att systematisera krav och kvalitetsnivåer medan viktningsmetodiken är känslig och bör användas med försiktighet tills mer erfarenhet nåtts. Liksom vid det teoretiska exemplet verkar skillnaderna beträffande livscykelkostnad och miljöbelastning mellan studerade alternativ relativt liten, varför den funktionella kvaliteten kan styra projekteringen. Detta är en viktig slutsats som bör stödja alternativ med god funktion.

Introduktion av ILCD, discussion, framtida arbete och slutsatser (Kap. 8-9)

Verktygslådan är färdig att användas i sin nuvarande form, i verkliga projekt eller som bas för vidareutveckling av ILCD teknik exempelvis för en byggherre, utvecklare av typhus eller konsult. Livscykelkostnader och miljövärdering kan göras med valfri noggrannhetsnivå.

I samband med detta kartlades projektdeltagarnas åsikter om ILCD och ingående metoder. Gensvaret från projektörerna i exemplen i kapitel 7, är i princip positivt även om en rad svårigheter påpekas. Vissa av dessa problem kan relateras till byggprocessens organisation snarare är till ILCD metoden.

Praktisk introduktion av ILCD i projekteringsprocessen diskuteras och presenteras. Behov och möjligheter till förbättringar i fråga data och metoder i verktygslådan diskuteras. Såväl det korta perspektivet berörs, som ILCD i en framtida projekteringsprocess baserad på flerdimensionella produktmodeller.

Rönen beträffande byggteknik är att byggnader ska vara anpassningsbara över tid för att undvika resursförstöring genom att de måste rivas i förtid, för att de ej motsvarar ändrade krav. Omgivningens klimat och övriga förhållanden kräver anpassning i fråga om byggfysiska aspekter som energiprestanda, innetemperatur och ljudisolering. Analysen av funktionella egenskaper klargör betongens roll i bärande och avskiljande konstruktionsdelar, i ett hållbart husbyggande.

Produktion, periodiskt underhåll och uppvärmning utgör de största delarna av livscykelkostnaden. När det gäller miljöbelastning dominerar uppvärmning. Dessa aspekter är i hög grad beroende av hur byggnaden projekteras.

Arbetet bekräftar att ILCD kan bidra till förbättrad funktionell kvalitet, kostnadseffektivitet och minskad miljöbelastning. Med hjälp av ILCD kan:

- Funktionella kvaliteter överblickas och klassificeras på ett systematiskt sätt.
- Konsekvenser beträffande kostnadseffektivitet och miljöbelastning, i livscykelperspektiv, av alternativa utformningar, klargöras.

1 INTRODUCTION

1.1 Background

A dwelling building is with few exceptions a long lasting object, representing a large value. With a rate of new construction varying between 20000 and 40000 flats per year in Sweden and a total stock of 4,3 million units, a dwelling building should be expected to last between 100 and 200 years.

The functional performance of buildings has a decisive impact on the quality of life of its inhabitants. The cost of housing is a large part of the private economy and from the public perspective buildings play a social as well as environmental key role in sustainable development. There are many different and sometimes also contradictory, requirements on a building such as functionality, economy, aesthetics, indoor climate and energy retention.

Often the design and procurement process of houses aim at minimising production costs with regard to a set of minimum requirements. This does not promote the optimum lifetime performance. If instead, design and procurement were based on holistic whole life appraisal, the functional performance and, thus, the overall quality and cost-effectiveness of the building could be enhanced. The total performance of a building is not only the sum of the performance of its components and systems but is also dependent on their interaction. Therefore, the building should be designed as a whole to obtain the optimum performance.

Integrated lifetime engineering is an approach to bridge the gap between the short-term design perspective and the long life nature and complexity of a building. Lifetime engineering comprises investment-planning, analysis of the current and future requirements on the building, life cycle performance prediction, facilities management and monitoring, and finally planning of disposal of the structures at the end of life. (After Sarja, 2003). The large overall importance of the built environment and construction activities in our society motivate the improvement and, if necessary, rethinking of the design process, to increase economical and environmental efficiency as well as functional performance.

The structural frame of a building and its interaction with the climate shell and the technical systems is of fundamental importance for the lifetime performance. In Sweden, as in many other countries, concrete is a frequently used construction material for multi-storey buildings. It is therefore of interest to consider if the properties of concrete can be further utilised to improve the performance of the building, over the entire lifecycle.

1.2 Aim

The aim of this work is to explore and indicate ways of designing a building frame in order to achieve the optimal overall lifetime performance of the whole building.

1.3 Scope

The investigation deals with the design of Swedish residential buildings. Most lifetime quality factors of a residential building are addressed. The study, however, focuses on aspects relevant in the context of design of the structural frame. This implies that there are some properties that are discussed but not included in the design model that is outlined. A specific task is furthermore to examine the properties of concrete with regard to building performance.

1.4 Method to address the aim and outline of the research tasks

Integrated Life Cycle Design, 'ILCD' is deemed to be a practicable approach for lifetime optimisation. A primary objective of this work is thus to advance the introduction of ILCD in practise.

The main ingredients facilitating ILCD are: Relevant performance criteria, life cycle data, methods to predict life cycle performance and means to rank alternative designs in relation to multiple requirements. This forms the background to the following research tasks:

i. To review the important attributes of dwelling buildings
ii. To determine how concrete relates to i.
iii. To review the ILCD concept for the application of dwelling buildings
iv. To compile a practical and transparent ILCD toolbox covering the key performance factors of dwelling buildings
v. To study and present how ILCD can be applied in the design of concrete multi-dwelling buildings through application of iv. on real projects

1.5 Contribution

The primary contribution of this work is the interpretation and practical utilisation of generic principles for holistic lifetime optimisation on a specific application. The end result is a pilot method for lifetime quality optimisation. The application selected is specific but the concept and tools are general. Important results are:

- A review and systemization of total lifecycle quality design criteria for residential buildings.
- An analysis of the behaviour of concrete in relation to the important performance criteria and conclusions on the advantages of concrete from the viewpoint of lifetime engineering.

- An open and transparent pilot toolbox for simplified Integrated Life Cycle Design that has been tested in real projects and is ready to apply in practise.
- A base for the introduction of holistic lifetime considerations in design practise.
- Conclusions on the usability, potential benefits and needs for future research of ILCD in practical design.

1.6 Research methods and organisation of the thesis

In Chapter 2 a state of the art review on methods for lifetime quality optimisation of buildings is given. The general concept is reviewed as well as specific tools for lifetime appraisal and assessment of performance.

In Chapter 3 the author interprets the findings from previous work in this field in order to obtain a base for the development of the pilot integrated life cycle design toolbox and to review lifetime quality factors. This part is the outline of the hypothesis that the research work is addressing and the chapter is ended with a list of research questions.

In Chapter 4 the primary factors relevant for the lifetime performance of dwelling buildings are identified. These lifetime performance quality factors are reviewed and systemised on the basis of studies of literature, including relevant standards, ongoing work in the field, current practise and a field survey. In this work the performance factors are defined as 'attributes'. Generally accepted criteria for the specific attribute are put forward if available and in other cases the author outlines criteria. The behaviour of concrete as structural material in relation to each attribute is analysed.

In Chapter 5 a toolbox for simplified integrated life cycle design is presented. The toolbox is a compilation of existing tools and tools developed by the author. The tools were verified by comparing computations with measurements and follow up on four existing Swedish residential buildings, 4 to 10 years of age and furthermore by studies of statistics on construction and operating costs and other sources of data.

In Chapter 6 a desktop study, applying the pilot toolbox, is presented. A theoretical building is designed with three alternative levels of total performance quality, and the consequences with regard to life cycle cost and environmental burden are quantified and compared. This study elucidates the general possibilities and shortcomings of the method and, moreover, provides information on this specific important question: What is the cost of increased functional quality?

In Chapter 7 a number of pilot application examples from real projects are presented. These were undertaken as part of the development of the methodology and cover different angles of application; that is, presents answers to different questions relevant during the design phase. By doing this, the toolbox could be refined step by step both with regard to content and usability. Moreover, barriers and advantages for the introduction of Integrated Life Cycle Design in practise were mapped. This part of the work is thus participative, and the researcher could observe and influence the design process.

In Chapter 8 the author discusses and presents the implications of, motivation for, and barriers to the introduction of integrated life cycle design.

In Chapter 9 general conclusions and recommendations for future work are given.

1.7 Definitions and abbreviations

Life time engineering	
Calculation horizon	The endpoint in time used by cycle appraisal.
Design life	Length of service life intended by the designer.
Environmental burden	The collected effect on environment caused by the environmental stressors, released by a product or process.
Environmental impact	The effect on one or more environmental safeguarding objects such as clean air, sustained ecosystems etc.
Environmental stressor	Chemical or non-chemical factors, relating to a product or process affecting the environment.
ILCD	Integrated Life Cycle Design. A design process model including physics, economy, health and environment with the objective to manage multiple requirements to control the life time quality of a product. After Sarja (2000)
LCA	Life Cycle Assessment. A group of tools intended for the assessment of environmental performance of a product or process, described in ISO 14040-43
LCC	Life Cycle Costing. Economic assessment of investment alternatives that considers all significant costs of ownership discounted over the lifetime of a product.
LCI	Life Cycle Inventory. Mapping of occurrences, relevant for the criteria, (e.g. costs) relating to a decision or alternative under study, over the life cycle.
Life cycle	The period of time between a selected date and the cut-off year or last year, over which the criteria (e.g. costs) relating to a decision or alternative under study, is assessed.

Life cycle appraisal	Prediction of life time performance with regard to economy or environment
Lifetime	Time period from the beginning of the investment planning until end of life management of a built object.
Lifetime engineering	'The holistic concept of predictive and integrated investment planning, design, management, monitoring and recovering of the built environment'. Sarja (2003)
Service life	Period of time after installation during which a building or its parts meet or exceed the performance requirements, cf. Section 2.3.
Service life planning	Preparation of the brief and design for the building and its parts to achieve the desired design life.
Service life design	Preparation of design of the facility and its parts to achieve the desired design life (target life) on the defined reliability level.
Sustainable	Satisfying functional, social, economical and environmental aspects both for the present and the future situation.
Other terms	
Attribute	One or a limited field of fundamental properties or characteristics of the building with regard to functional performance, environmental performance or economy.
Functional attribute	Referring to Figure 3.1 functional here defines all the lifetime quality factors that represent the benefits of the building, that is, all attributes except for the lifecycle cost and environmental burden.
Client	The entity initiating, designing, procuring, accepting, owning and using the building. It is acknowledged that depending on type of building, type of ownership and market situation, this simplification is more or less valid. The restriction implies basically either that the owner, client and user is the same entity or that there is a linear relationship between user satisfaction and value for the owner. This simplification can be argued. There is however no restriction to expand the model presented in this work to include additional stakeholders.
Construction cost	Costs for on- and offsite production, normally relating to the responsibility of the contractors.
Development cost	Costs for land, design, municipal connections etc. equivalent to the Swedish 'Byggherrekostnad'. Sometimes referred to as 'acquisition cost'.
Infill	Parts of a building specific to the flat and systems that need to be exchanged some times during the life cycle of the building
Support	Parts of a building that are common to all users and that in principle will last as long as the building itself such as the structural frame and normally most of the climate shell.
Total project cost	All costs that occur for a building project including development and construction costs.

2 INTEGRATED LIFE CYCLE DESIGN - STATE OF THE ART REVIEW

This chapter reviews previous and ongoing research and current practice relating to integrated lifetime optimisation of buildings. The full-blown holistic approach joins the functional performance quality, life cycle economy and environmental burden for a combined analysis and optimisation. This state of the art review also encompasses limited models dealing with specific aspects, and furthermore supporting methodologies, that are of relevance as a background to this thesis.

2.1 Background to holistic or integrated life cycle design

Integrated life cycle design, 'ILCD' belongs to the ideas collected under the umbrella of 'Lifetime engineering'. According to Sarja (2003a) lifetime engineering is a 'holistic concept of predictive and integrated investment planning, design, management, monitoring and recovering of the built environment'. Integrated lifetime engineering is thus a methodology to foresee, optimise and control the requirements on buildings such as shelter, functionality/usability, safety, health, comfort and also economy and environment, over the life cycle. The optimisation methodology is applied both by interpretation, analysis and synthesis of the client's requirements on the building as well as by final ranking of the available design alternatives.

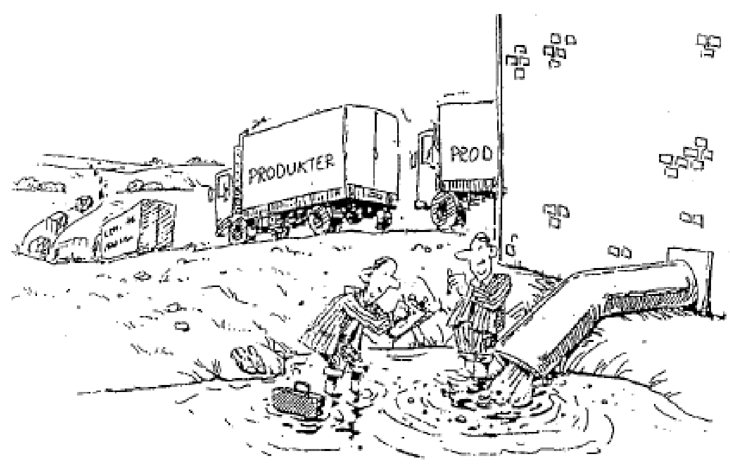


Figure 2.1 Traditional production oriented approach, focusing on the environmental burden of production rather than on the products. (SOU, 1989)

The need to address and integrate a wider range of objectives than price and performance, by product development, can be traced to the growing awareness of the global environmental or ecological constraints that our civilisation is facing. During the 1980s the focus on environment thus broadened from plant to product and the market began to take an interest in environmental performance of products. Thus the life cycle performance, including the final disposal had to be considered by product development (Ryding 1995), expanding the former product oriented approach described by Figure 2.1.

Design methods in this context can be sorted in different orders of complexity:

i. Estimation of the economical and environmental lifetime consequences of a product, which can be done by methods such as LCC and LCA.
ii. (i) Including some kind of evaluation of the functional performance. Terms such as '*eco-efficiency*' are then often applied, cf. the CASBEE example in Section 2.2.
iii. A holistic lifetime design approach illustrated in Figure 2.2, where economy and environment as well as functional performance are taken into account.

For complex objects such as buildings it is presumed that a holistic design mode is necessary to achieve an optimal lifetime quality, and furthermore this is in line with the idea of 'sustainable' development.

The World Commission on Environment and Development, in 1987, in the document *Our common future* puts forward the often-sited description of sustainable development as 'fulfilling the needs of the present without compromising the ability for future generations to fulfil their own needs'. The definition of sustainable development as the converging area of the three fields representing: Economy, ecology and social aspects became generally acknowledged during the 1990s and is described by, for instance, Ryding (1995) and Barrow (1997). Cf. Figure 2.2.

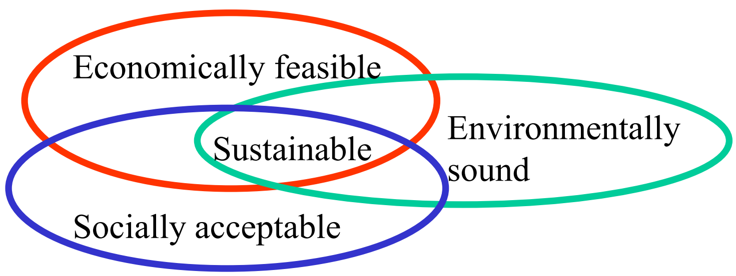


Figure 2.2 Sustainable development after Ryding (1995) and Barrow (1997), whereby economical, environmental and social requirements all are satisfied.

A large part of the ongoing research and development in the building sector is relevant for sustainable development, referring to the definition above. The first conference on sustainable construction held in the U.S.A in 1994, defined sustainable construction as 'The creation and responsible maintenance of healthy built environment, based on ecological principles, and by means of an efficient use of resources'. This underlines the importance of addressing functional aspects, in this case health, in parallel to global environment. Hill and Bowen (1997) presented a definition of sustainable construction referring to the four fields: Social, economical, ecological and technical. Many of the functional attributes of the building, such as shelter, safety and health, belong to the social field. Economy here refer to the full cost principle implying that, for instance, energy or transport expenses should carry also any related environmental cost. The ecological field covers the long-term balance of natural resources and environment. Technical sustainability implies durable and functional systems and structures and it is pointed out that buildings should be designed to facilitate adaptation for changes in use over the lifecycle. Kohler (1999) states that the Roman amphitheatre in Nimes in France, is a perfectly sustainable building referring to its continuous use for different applications during more than 2000 years. The example is interesting. However, it could be argued that the economical feasibility and social acceptability, with regard to the production phase, is difficult to assess so long time after.

Figure 2.3 Example of sustainable buildings according to Kohler (1999): The Roman amphitheatre in Nimes, which has been constantly in use, for different purposes, for more than 2000 years.

CIB[3] in the mid 1990s took on a role to coordinate and promote development of sustainable construction through its working commissions, publications and conferences. The theme of the 14th CIB World Building Congress in Gävle, Sweden, 1998 was *Construction and the Environment.* Several contributions to this congress and also in the ongoing CIB work relate to ILCD In 1999 CIB established an Agenda 21 for sustainable construction with the aim to be an intermediary between global environmental commitments and agendas that are being developed nationally or by organisations specifically for the construction sector.

[3] The International Council for Building Research Studies

The first international conference dedicated to Integrated Life Cycle Design of buildings was the RILEM[4]/CIB/ISO[5] symposium *Integrated Life-Cycle Design of Materials and Structures*, *ILCDES 2000*, in Helsinki. In 2003, this was followed by the RIL[6]/RILEM/CIB symposium *Integrated Life-Time Engineering of Buildings and Civil Infrastructures, Materials and Structures, ILCDES 2003*, in Kuopio, Finland. Reviewing the contributions to these conferences it can be noted that a majority of the design oriented work presented, is limited to one specific supporting topic such as life cycle costing, durability of materials, environmental assessment and so on. Examples of work where also borders are crossed in pursuit of a general holistic mode are presented below.

To summarize: The broadened and increased environmental concern, expressed by the introduction of the sustainability concept, has been the driver for introduction of integrated life cycle design. ILCD enables products to be developed, fulfilling the public social and environmental needs at the same time as the requirements of the client, with regard to function and economy.

2.2 Integrated life cycle design methods

Ryding (1995) describes integrated design, or what he defines as 'sustainable product development', from an industrial perspective as the merger of two principles:

i. 'Integrated product development', which is the combination of focus on customer requirements and on rational production. To his end Ryding suggests QFD, cf. Section 2.6.1 and LCC, cf. Section 2.4.
ii. 'Environmentally oriented product development', having the objective to decrease the life cycle environmental burden of the product, whereby LCA is the suggested engineering tool, cf. Section 2.5.

Ryding stresses the importance of a well-defined system theory as a base for holistic product development. Two dimensions are particularly important in this:

- The time dimension covering lifetime endurance of materials and components.
- The structural dimension covering the functional performance of the end product and its components, and the processes involving transformation of energy and materials.

[4] The International Union of Testing and Research Laboratories for Materials and Structures
[5] The International Standardisation Organisation
[6] The Association of Finnish Civil Engineers

These dimensions should be combined in the practical design work so that products are optimally balanced with regard to cost, environment and functional performance for the present situation, but also with consideration to openness for future improvement. Ryding points out that a broad range of competences, therefore, are needed in the early product development phases. This is an important remark that has implications on the organisation of the design process. Ryding primarily describes and relates to experience from integrated product development in the manufacturing industry. The general principles and tools suggested by Ryding are, however, also relevant for the construction sector.

Sarja has published works relating to ILCD on buildings and civil engineering structures since the early 1990s. A comprehensive description of the subject is presented in *Integrated Life Cycle Design of Structures* (Sarja, 2002).

Sarja (2004) classifies the requirements on buildings in the four generic groups, presented in Figure 2.4.

1 Human requirements • functionality in use • safety • health • comfort	2 Economic requirements • investment economy • construction economy • lifetime economy including operation and end of lifecycle
3 Cultural requirements • building traditions • life style • business culture • aesthetics • architectural styles and trends • image	4 Ecological requirements • raw material economy • energy economy • environmental burdens economy • waste economy • biodiversity and geodiversity

Figure 2.4 Generic requirements on buildings according to Sarja (2004).

Generic requirements must be translated and transferred to specific requirements that are relevant for the object in question. Sometimes the specific requirements address different generic requirements at the same time. For example the functionality in use, in the human requirements field, responds to certain performance with regard to the economical and environmental fields, compare Figure 2.4. In Chapter 4 generic and specific requirements on dwelling buildings are discussed.

The methods needed to design a building according to all the requirements are the traditional design tools complemented with some methods for life cycle appraisal and optimisation as discussed below. Sarja (1998) has presented the overview on requirements and methods shown in Figure 2.5. The terms applied by different authors may diverge. While Sarja uses 'performance' as one particular field of requirements, the term is in this work utilised to esteem the quality of any specific aspect, such as environmental performance or functional performance.

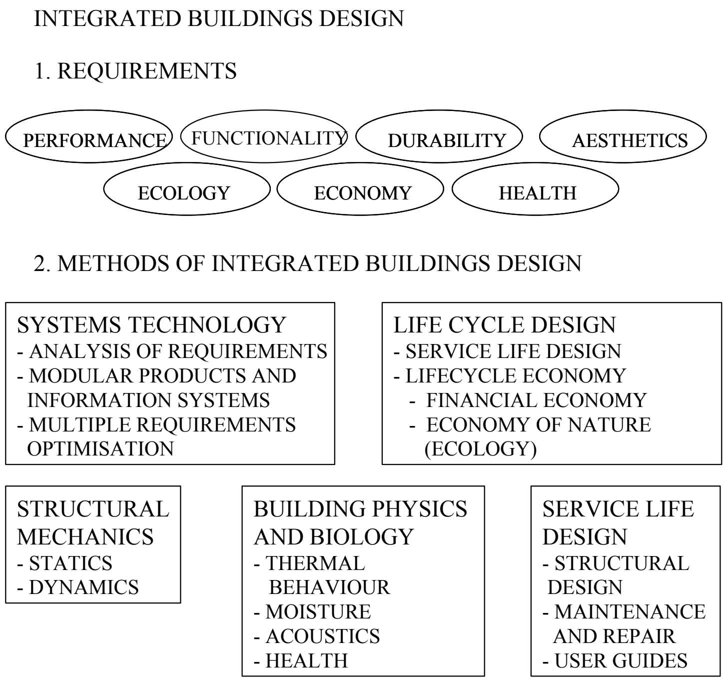


Figure 2.5 Requirements and methods for integrated building design according to Sarja (1998).

There are several pilot design tools that address function, economy and environment in a more or less holistic way. So far the methods have been applied in practice primarily in pilot cases and for projects with a particular environmental profile. Examples of integrated tools are 'ECOPROP' (Leinonen and Houvila, 2000) the 'GBTool' (iiSBE, 2003), the Japanese 'CASBEE' (Murakami et al, 2002) and 'BEES' (Lippiat, 2000). Common to these systems are that they are requirement and decision management tools and do not, or only to a small extent, include instruments for quantitative assessments or predictions. Benchmarking values on costs or energy use are, however, provided in many systems.

CASBEE 'Comprehensive Assessment Systems for Building Environmental Efficiency' covers three **Quality** indicators (**Q**), and three **Load** indicators (**L**), according to Table 2.1. BEE – Building Environmental Efficiency - is expressed as the quotient between **Q** and **L**. Each category in Table 2.1 is divided into 2 to 6 sub-categories, with a total of 80. These are given a score between 1 and 5 for the specific building. This is weighted in two steps: Firstly the individual sub-category is assigned a specific normalised weight and secondly the Q and L respectively are calculated with formulas that include a weighting. The ratings for Q-1, Q-2 and Q-3 are given the weight of: 0,50, 0,35 and 0,15 respectively and the ratings for L-1, L-2 and L-3 are given the weight of: 0,50, 0,30 and 0,20 respectively.

Table 2.1 Quality and load indicators according to the CASBEE environmental efficiency assessment method (Murakami et al, 2002)

Q. Building Environmental Quality and Performance		L. Building Environmental Burdens	
Indicator	Category	Indicator	Category
Q-1 Indoor environment	Noise and acoustics	L-1 Energy	Thermal load
	Thermal comfort		Natural energy utilisation
	Lighting		Efficiency in building systems
	Air quality		Efficient operation
Q-2 Quality of service	Service ability	L-2 Resources and materials	Water resource
	Durability		Eco-materials
	Flexibility & Adaptability	L-3 Off-site environment	Air pollution Noise and odours
Q-3 Outdoor environment on site	Maintenance and creation of ecosystems		Wind damage
			Lighting damage
	Townscape and landscape		Heat island effect
	Local characteristics and culture		Load on local infrastructure

The designed or assessed existing building is positioned in a graphical presentation according to Figure 2.6, with 5 BEE classes ranging from the lowest C, to the highest S. Current practice for new buildings are positioned in the centre of the square and defined as ‘standard’.

The CASBEE method contains a very thorough assessment of the functional performance and a very illustrative representation of the result in terms of environmental efficiency. Economy is, however, not considered, and furthermore there are no quantitative instruments included in the system. Thus, any estimation of for instance energy requirements or durability for a specific building is not supported. The result sheet however contains a section where this quantitative information may, optionally, be tabled.

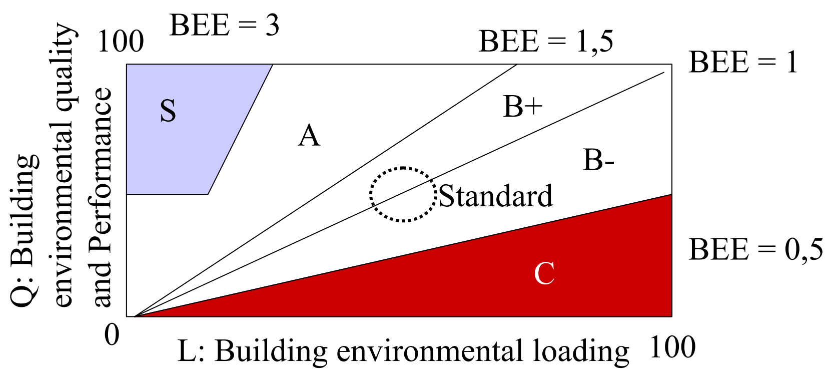


Figure 2.6 Presentation of building environmental efficiency according to CASBEE. (Murakami et al, 2002). C is the lowest and S the highest environmental efficiency. 'Standard' refers to current practice by new production.

The GBTool is a very extensive and detailed assessment method. It has a decision support module based on a system of voting within the design team, and a method to benchmark a specific project in comparison with other buildings. GBTool has a lot of similarities with the CASBEE method but includes also the life cycle cost. The GBTool uses as scale from –2 to 5 where 0 represents minimum (norm) level for new buildings, 3 best practice and 5 best available technology.

Figure 2.7 GBTool – concluding result diagram. 'Loadings' indicate global environmental aspects such as green house effect or ozone depletion. 'IEQ' = Indoor environmental quality, 'Service Quality' refers to aspects such as access to daylight and flexibility. O indicates minimum quality for new buildings according to norms and 5 the best available technology. (iiSBE, 2003).

In Diagram 2.7 the summary of results of GBTool, applied on a North American office building, is presented. This diagram shows the seven major assessment categories. The result is also tabled in a very detailed and comprehensive, quantitative report covering a total of 112 aspects, including quantitative values for benchmarking. In Table 2.2 some examples from this are given. As the CASBEE method, GBTool requires other instruments such as energy balance programmes, life cycle cost programmes and data for qualitative calculations, to provide the input data for the assessment.

Table 2.2 Part of the GBTool assessment report for a specific North American project. (iiSBE, 2003).

	Other General Building Data	Bmark	Design	Units	Design/ Bmark
R15	Total construction cost	$4 480 000	$5 600 000	$US	1,25
R16	Predicted total annual energy cost	$43 000	$26 000	$US/year	0,60
R17	Predicted annual other operating cost	$17 920	$22 400	$US/year	1,25
R18	Predicted annual maintenance cost	$23 296	$19 600	$US/year	0,84

	Normalized General Building Data	Normalized by net area		Units	Normalized by net area and occupancy		Units
		Benchmark	Design		Benchmark	Design	
R70	Annual consumption of delivered energy (presumed purchased)	929	474	MJ / m^2 * yr	10 696	5 452	(MJ/m^2) / (kaph/m^2) *yr
R71	Annualized embodied energy for above- and below-grade structure and building envelope	49	49	MJ / m^2 * yr	564	560	(MJ/m^2) / (kaph/m^2) *yr
R72	Total of annualized embodied energy and annual delivered energy	978	522	MJ / m^2 * yr	11 260	6 012	(MJ/m^2) / (kaph/m^2) *yr
R73	Total primary non-renewable fuels used on-site and for generation of electricity, annual basis	1 074	554	MJ / m^2 * yr	12 362	6 379	(MJ/m^2) / (kaph/m^2) *yr
R74	Predicted Greenhouse Gas Emissions from annual operations	85,0	53,6	Kg / m^2 * yr	979	617	(Kg/m^2) / (kaph/m^2) *yr
R75	Crude estimate of annualized embodied GHG emissions, Kg. CO2 equivalent (based on kg CO2 equivalent per GJ.)	4,1	4,0	Kg / m^2 * yr	47	46	(Kg/m^2) / (kaph/m^2) *yr
R76	Predicted total Greenhouse Gas Emissions from annual operations and annualized embodied emissions	89,1	57,7	Kg / m^2 * yr	1 025	664	(Kg/m^2) / (kaph/m^2) *yr

ECOPROP is a requirement management tool. It works with five preset performance levels, and uses a conflict handler in a spreadsheet model structured as QFD, cf. Section 2.6.1, to prioritise the lifetime quality aspects. The tool is based on a generic building property classification developed by VTT[7] in Finland.

BEES, 'Building for Environmental and Economic Sustainability', is a tool to compare building products, or whole existing buildings, with regard to global environment, indoor environment and life cycle economy. It is based on the international standards for environmental assessment, life cycle costing and multiple attribute decision analysis.

[7] VTT: The Technical Research Centre of Finland

The Swedish EcoEffect method (Glaumann, 2001) covers energy use, material use, global as well as indoor environment and life cycle cost. However, costs in this method refer only to the environmentally related costs, such as energy or waste disposal costs or the extra investment to obtain the specific environmental benefit. As in the GBTool the specific building is benchmarked in relation to other buildings, according to the scores with regard to the five parameters listed above.

Sterner (2002) has studied how environmental performance and life cycle costs can be further utilised by procurement of buildings and envisaged a practical method to this end. Environmental performance is based on the energy use during operation of the building and assessed via a set of four environmental impact categories that are connected to the national Swedish environmental quality objectives, cf. Section 2.5.2. An environmental index factor is thus determined. This is taken into account together with investment cost and lifetime cost, via a conversion factor translating the environmental impact into an economical cost. The client decides the conversion factor, and thus the weight attached to environment. Sterner concludes that the application of LCC by procurement can give clients better profits, and that the environmental assessment model can be used to justify the selection of environmentally friendly alternatives.

Löfsjögård (2003) presents an optimisation model for concrete paving of roads whereby a socio-economic optimisation is the end objective. The model is presented in a chart where is pavement system, material and surface, and their specific properties and functional performance. This is linked via effects, such as fuel consumption, road cost and environmental impact, to an aggregated socio-economic efficiency. Calculation examples are also presented.

Zeiler (2004) describes a Dutch initiative to develop an 'Integral design methodology', to reach higher synergy between different disciplines of the design team in the conceptual phase. The focus here is improved energy performance and indoor environment by removing methodological and organisational barriers between architect, HVAC- (Heating Ventilation Air Conditioning), and structural engineers. Key elements are the introduction of different specialists early in the project and the application of a morphological mind-map, whereby the building is functionally decomposed. Aspects such as energy storage in the structure, or the indoor climate relevance of the façade, are thus possible to address.

2.3 Life Cycle planning and book keeping – some general principles

This section presents some common priciples and practices related to life cycle accounting of environmental burdens and economy, related to a product or service.

In reality the borderline between economical and environmental bookkeeping is not distinct as environmental burdens to some extent are conveyed to the consumer, as taxes or fees on, for instance, consumption of energy, scarce natural resources, or waste disposal. In the ideal situation where the environmental cost is distributied on to the user fully and consequently, no distinction should be necessary as everthing is valued in money. Looking from the life cycle appraisal perspective there is, however, one important objection: According to economical calculation procedures the value of a future expenditure or earning is normally regarded as smaller than if it had occured today. The reduction is determined by the discount rate and with a higher discount rate the significance today of a future occurrence decreases. With regard to environment this time related impact reduction is usually lower or non at all. It should reflect if the the stress on environment from the particular occurrence has changed in the future. Tupamäki (2003) indicates four different discount rates: 0% for the environmental, 3% for national, 6% for the state and 9% for the business perspectives respectively.

Common to both economical and environmental life cycle appraisal is the inventory part, where the product is tracked from cradle to grave and all relevant occurences, for example maintenance and use of energy, are mapped. For a product of high complexity and long life span such as a building the inventory is an extensive task, when performed in detail.

The inventory is thus a core in a whole chain of activities such as quantity surveying, service life design, maintenance planning, and economical and environmental assesement of alternatives. It follows the project from the initial sketches by investment planning over design, tendering and construction to facility management.

A crucial item of the inventory is the length of the life cycle or the ‘service life’, compare Section 3.3.6. In principle ‘life cycle’ and ‘service life’ can be understood as the same. However, most authors define life cycle as the entire life from cradle to grave for an object, while service life refers to the time from start of use to end of its use. A life cycle can have different scopes. Bejrum (1991) suggests that the life cycle of the object and not the life cycle of a specific ownership, should be used by normal practice of LCC, to avoid any irregular effects of tax or property value change, cf. Figure 2.8.

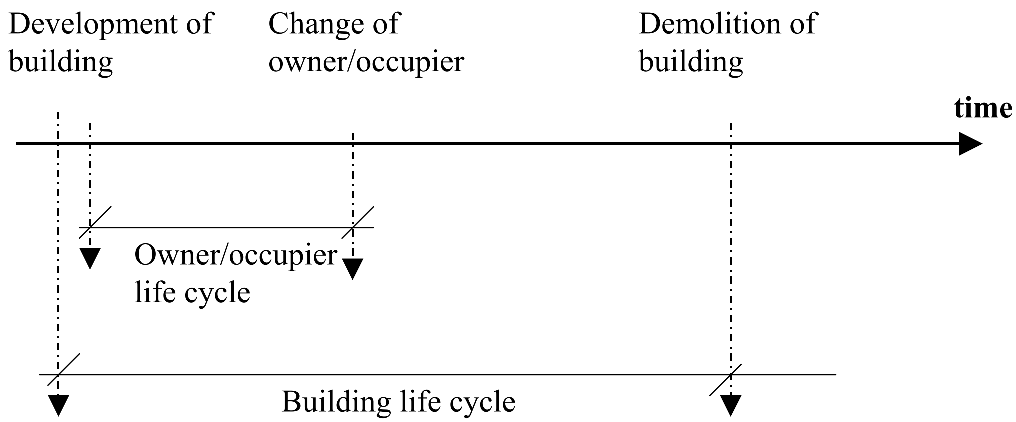


Figure 2.8 Different types of life cycles. After Bejrum (1991)

According to ISO (2000) there are three kinds of service life for construction assets:

- Technical: The time until the intended purpose of a product cannot be served.
- Economical: The time until it is economical to exchange a product.
- Functional: The time until the need of the user has changed so that a product is not longer wanted.

Figure 2.9 Indicates that the technical life cycle is often not utilised to its full extent because of functional or economical obsolescence, which is discussed further in Section 4.9. One basic objective of service life design and ILCD is to coordinate life cycles and service lives of components, systems and the whole building. Service life design is discussed in Section 4.7.

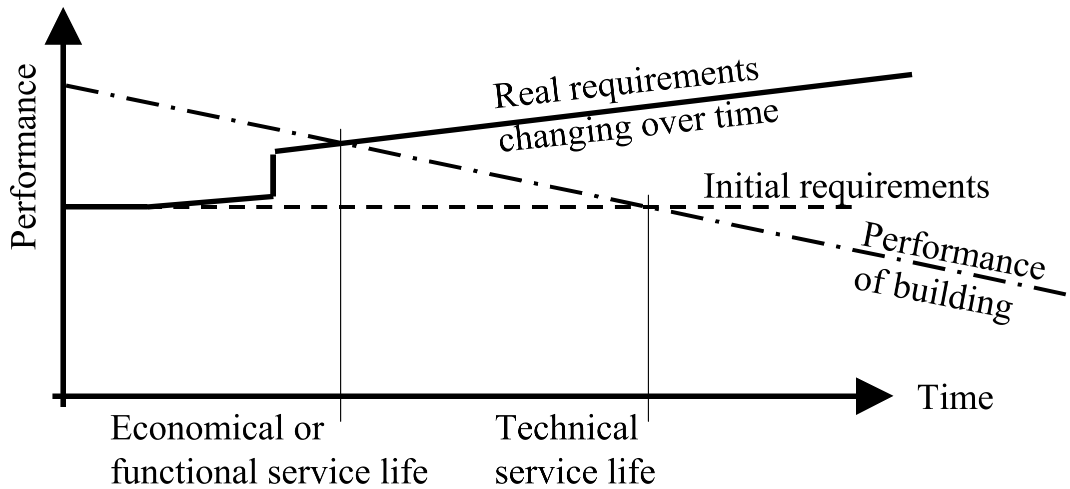


Figure 2.9 Obsolescence of the building occurs when the economical or functional requirements on the building exceeds the performance before the end of the technical service life. Requirements on a building may increase, decrease or remain constant over time.

2.4 Economic life cycle appraisal tools

2.4.1 General

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'.

In many applications, the revenues are also taken into account (Dale, 1993). In practice, it is difficult to exclude revenues, as there are normally such consequences related to any decision, from the owner's perspective. The initial and operating costs are seen in the same context as rent and the residual value and, therefore, an expression such as life cycle economy would be more appropriate. The term 'Whole Life Costing', abbreviated 'WLC', has been introduced in later years as an alternative expression with equivalent meaning. An international standard for Whole Life Costing is being developed by ISO. 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'. Tupamäki (2003) however states that this discussion on wording only contributes to confusion, as the term LCC has been understood and used in practise for a long time. LCC is used in this study.

Stone, at the Building Research Establishment, introduced LCC in the British building industry during the 1950s, with the term 'cost-in-use' (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*.

STANDARD CATEGORIES				
REAL ESTATE AND PROPERTY MANAGEMENT				
	FM – Facilities Management			
1 **Capital-cost**	2 **Management cost**	3 **Operating cost**	4 **Maintenance cost**	5 **Development cost**
10 (Unused)	20 (Unused)	30 (Unused)	40 (Unused)	50 (Unused)
11 Project cost	21 Taxes	31 Daily operation	41 Scheduled maintenance	51 Current rebuilding
12 Residual cost	22 Insurance	32 Cleaning services	42 Replacements	52 Official rules and requirements
13	23 Administration	33 Energy	43	53 Upgrading
14	24	34 Water and sewage	44	54
15	25	35 Waste disposal	45	55
16	26	36 Watchguards and security	46	56
17	27	37 Outdoor	47 Outdoor	57 Outdoor
18	28	38	48	58
19 Miscellaneous	29 Miscellaneous	39 Miscellaneous	49 Miscellaneous	59 Miscellaneous

Figure 2.10 Cost categories for LCC of buildings according to Norwegian standard NS 3454, 'Life cycle costs for building and civil engineering work – Principles and classification'

The British Standards Institution presented a standard, BS 3811, in 1974, describing the life-cycle phases from design to replacement, which fits well with the organisation of LCC (and LCA cf. Section 2.5). 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 a Norwegian Standard, NS 3454, *Life cycle costs for building and civil engineering work – Principles and classification*. In Figure 2.10 the cost categories from the Norwegian standard is displayed to indicate the relevant cost items for LCC on buildings.

In Sweden, LCC has been practiced 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. Haugbolle (2003) have reviewed the state-of-art of life cycle economics in the construction sector in the Nordic countries and concludes the following, which is in line with the experience gathered in this research work:

- Across the Nordic countries there are several different LCC classifications in use. Norway is the only country with a national standard.
- There are several IT-tools available to calculate life cycle costs for different applications such as facilities management or single-purpose optimisation (often energy).
- Key figures for benchmarking are available.
- Several networks for actors interested in life cycle economics have been established 'but besides these clusters of committed actors, the majority of the real estate and construction cluster do not care much about life cycle economics'

There are several models and tools for LCC available. Though the underlying theory is the same, the methods are used for different purposes and the user should be aware of their limitations. In Section 2.4.3 – 2.4.7 some of the most applied methods are reviewed.

The concept of adding investment and operating costs for the choice of constructions was used by the City of London already by the end of the 19th century. Here either a macadam pavement, or a more expensive to produce but more durable stone paving, was selected depending on the traffic load in the particular case. Records with experience on maintenance of pavements 40 years back were used to establish the operating costs for the alternatives, for different traffic intensities.

The calculation procedures used by LCC 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 estimate the economic results of investments.

2.4.2 The discount rate

The discount rate is of significant importance for any LCC-calculation with a time horizon longer than 3-5 years, irrespective of which of the methods described below is used. A low discount rate emphasizes the value of a future event. With the discount factor 0 time becomes irrelevant, cf. Section 2.3.

In principle the discount rate should be equal to the alternative cost of capital. Therefore it is different for different entities and varies over time. The state may for instance use the interest on state bonds. This can be regarded as the lowest possible discount rate. A company may set the discount rate to the:

- Cost to use saved capital, which may be equal to the interest rate for long-term loans on the capital market (lowest discount rate).
- Yield of other company investments (highest discount rate).

Companies often determine the discount rate on the basis of the mean cost of capital and the risk of the particular investment. The capital in the company normally is a combination of own and foreign capital. The mean cost of capital is the weighted average of the expected profit from two categories. The discount rate should thus match the expected yield of the company to ensure its long-term survival. A high-risk venture, furthermore, motivates a higher discount rate than a secure investment.

The discount rate can be determined using assumptions of the real interest rate and the change of the price of the particular item in relation to the consumer price index, 'CPI'. The real interest rate is defined as the nominal interest rate minus inflation according to the CPI. Compare Section 5.11.1.

2.4.3 Present Value

The idea of the method is to calculate the total capital value, or 'net present value', of an investment, at a specified point in time, after satisfying a selected discount rate (SK, 1996). In case both costs and revenues are included, the investment is profitable if the net present value is positive. When comparing alternative investments the highest net present value is advantageous. If there is no profit involved the least negative present value is preferred. Alternatives with different working life are normalised by attaching residual values and the end of calculation period.

The method is usually applied for large and long lasting one-time investments with several future consequences that need to be aggregated and assessed. It is easy to interpret and well suited for permanent buildings and infrastructures. The only weakness of the method is that if the amount of capital for the investment is restricted and the alternatives have significantly different investment cost and net present values, the alternative with higher investment costs may be unduly preferred in comparison with an alternative with smaller investment. In such a case the profitability index is a better indicator.

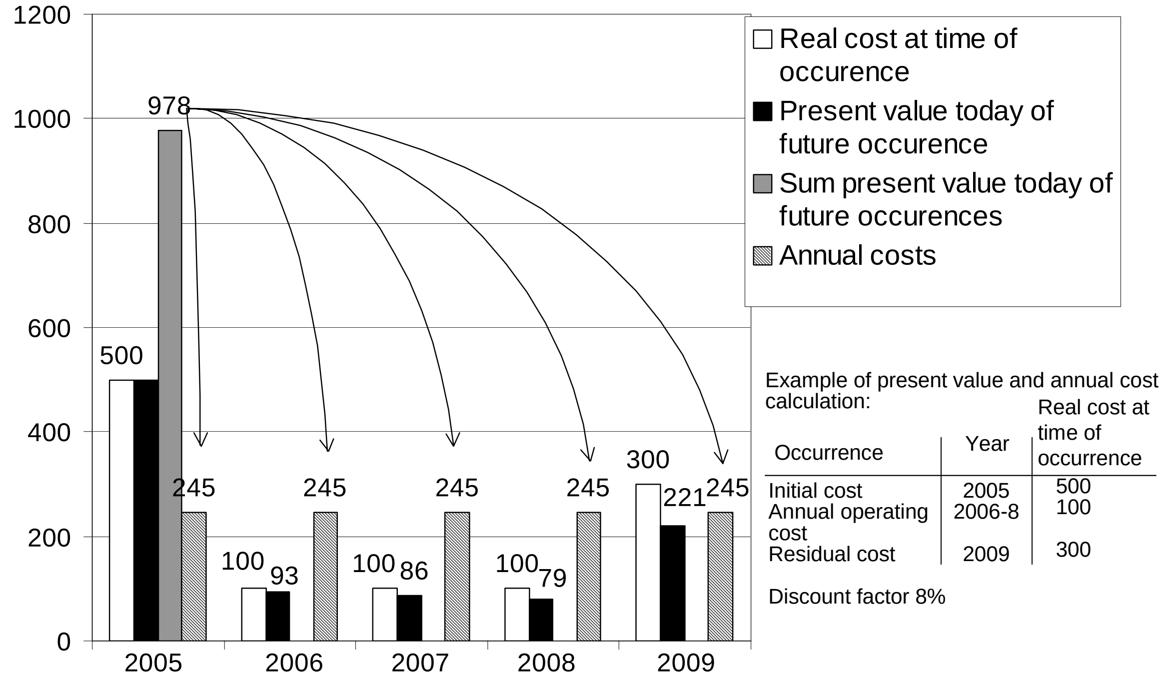


Figure 2.11 Example of LCC calculation. Present value and annual cost.

2.4.4 Profitability index

Using the profitability index the net present value is divided by the initial investment. The quote indicates which alternative that yields the highest profit in relation to the invested capital (SK, 1996).

2.4.5 The annuity method. 'Annual cost'

The annuity method is used to sum up all costs and distribute them evenly to an equal annual mean cost over a specified time period (SK, 1996), cf. Figure 2.11. Comparing alternatives the annuity method will give the same result as the present value. The method provides information on the average annual cost or profit and can be utilised for instance to establish the rent for a building or flat. The method is also practical to use when comparing investment alternatives with different lifespan, as it is not necessary to use the same calculation horizon.

2.4.6 Internal rate of return

By this method, both costs and revenues are normally included. The internal rate of return is defined as the discount rate that gives the present value = 0 is calculated (SK, 1996). The investment is deemed to be profitable if the internal rate of return is higher than the discount rate of the investors. This method is not suitable for comparisons between alternatives as the internal rate of interest, which is used to move costs and revenues in time, is the result of the calculation and thus a theoretical interest rate. This may differ from the discount rate that is used by the investor and thus distort a comparison between alternatives.

2.4.7 Simple payback

The payback or payoff method is used in particular by the manufacturing industry to guide short-term investments and is the simplest way to establish profitability (SK, 1996). The shorter time to balance the investment, the more profitable the investment is. The basic form, simple payback, does not take interest rate into account. The method is mostly used as a rough estimate to distinguish if an investment is profitable or not, which is the case if its service life is longer than the payback time. The method is short-termed, excluding inflation, interest and cash flow and favours investments with large early positive yields.

2.4.8 Value or cost of a building at the end of the life cycle

In a full LCC a value or cost is attached to the product at the end of the life cycle. That is referred to as ‘residual costs’ in Figures 2.10 and 2.11. For a dwelling building this could be the sales value of the house, or the cost to demolish and handle the final disposal of materials and components. The second hand value of a multi-dwelling building is governed by technical as well as external factors. It is thus difficult to make relevant predictions concerning differences in theoretical value or sales price many years ahead, for alternative designs. The general quality level of all attributes plays an important role. Attributes such as adaptability and robustness are normally particularly interesting.

Because of the long life span of dwelling buildings the economical consequence of what is happening at the end of life 100 years ahead, is seldom significant when comparing alternatives, by calculation of present value at the design phase. With a long calculation horizon the differences in cost of demolition and final disposal as well as second hand value become so small that they in principle can be neglected in a comparison between alternatives, cf. Diagrams 5.7, 5.8. Other tools than present value calculations must therefore be applied when these important aspects are considered.

2.5 Environmental life cycle appraisal tools

2.5.1 Introduction to Life Cycle Assessment - LCA

The term Life Cycle Assessment, ‘LCA’, has been reserved for environmental life cycle appraisal even though the term indicates a wider scope. LCA contains elements that are methodological parallels to LCC. For more detailed information on LCA refer to, for example, Baumann and Tillmann (2004).

Life Cycle in this context does not necessarily imply that a whole life cycle ‘Cradle to grave’ is studied. The same methodology can be applied for a part of the life cycle. Typically the environmental burden of production of a product can be assessed, which is defined as 'Cradle to gate', where gate refers to gate of a plant or 'Cradle to site' if transportation to the customer is included.

Environmental requirements cover a wide range of issues relevant for the building sector and the built environment, cf. Figure 2.12.

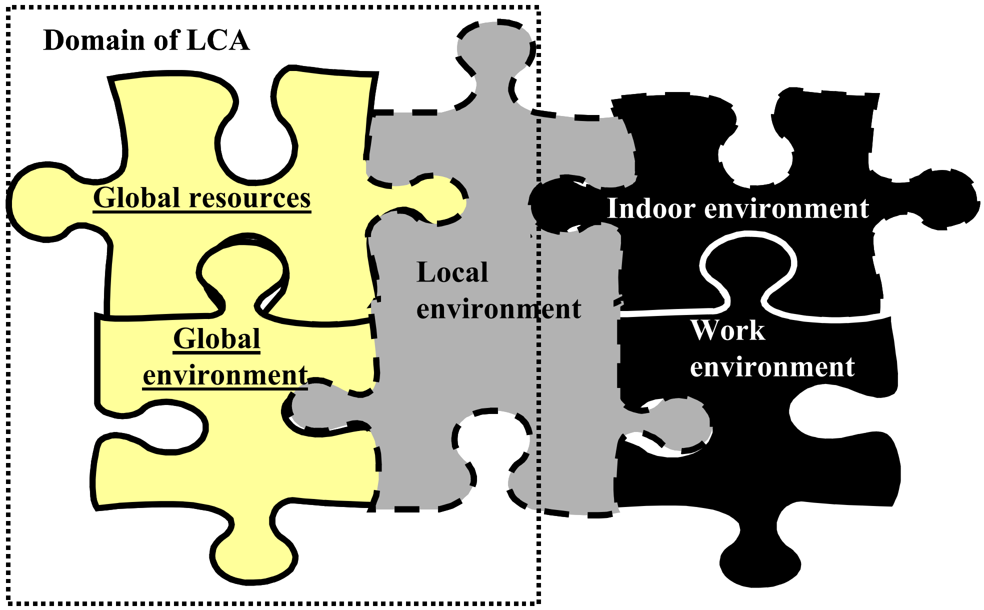


Figure 2.12 Environmental aspects relating to construction and the built environment and the scope of LCA. Examples of stressors for: Global environment: Substances that cause ozone depletion or global warming. Local environment: Toxic substances, noise or dust ('environmental stressors') released to ambient of building, road or plant.

Figure 2.12 indicates a total environmental perspective and the aspects that normally are included in LCA (Ryding, 1995):

- Global resources, typically energy and materials.
- Chemical impact factors on ecological balance and health affecting global or local environment.
- Non-chemical impact factors such as radiation, noise and dust affecting global or local environment.

The possibility to include also the indoor environment has been discussed by Jönsson (1998). One problem is to connect environmental impacts that affect a limited number of people, such as the occupants of one building with aspects that are of global or regional character.

Among the early users of LCA were the Midwest Research Institute and the Coca Cola Company. In a study from 1969, they compared environmental burden 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 (Ryding 1995).

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. From the early 1990s, LCA gradually became more widespread and the method was 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) for LCA.

2.5.2 Brief overview of the LCA procedure

The method of LCA normally consists of the following steps according to Ryding (1995) and the SETAC 'Code of Practice' (Consoli et al, 1993), cf. Figure 2.13:

i. Definition of goal and scope of the study.
ii. Life Cycle Inventory, 'LCI'. Here the process or product life cycle is described and occurrences with environmental relevance, cf. list of aspects above, are mapped and quantified, analogous to the mapping of economical consequences by LCC.
iii. Assessment of environmental impact, which is divided into:
   - Classification of the relevant impact categories. These are typically related to general environmental quality objectives with regard to human health, ecological balance and resource utilisation.
   - A characterisation model that links the physical environmental stressors, for example NO_x emissions, to the impact categories. The impact is calculated as the sum of impacts of relevant stressors with regard to each impact category. It is expressed as the relation to an appointed reference stressor for the specific category. For instance CO_2 is the reference for global warming. The influence on global warming of Methane, CH_4, is 56 times as strong as CO_2. 1 unit of CH_4, has thus the global warming potential of 56 (CO_2 units). The total impact, of the product or process examined, is also referred to as the *Global Warming Potential*, *Acidification Potential* etc.
   - Valuation and normalisation by weighting indexes, which represent a prioritisation between the impact categories, cf. Table 2.3, to obtain an aggregated result.
iv. Interpretation of the result and analysis of improvement of the product.

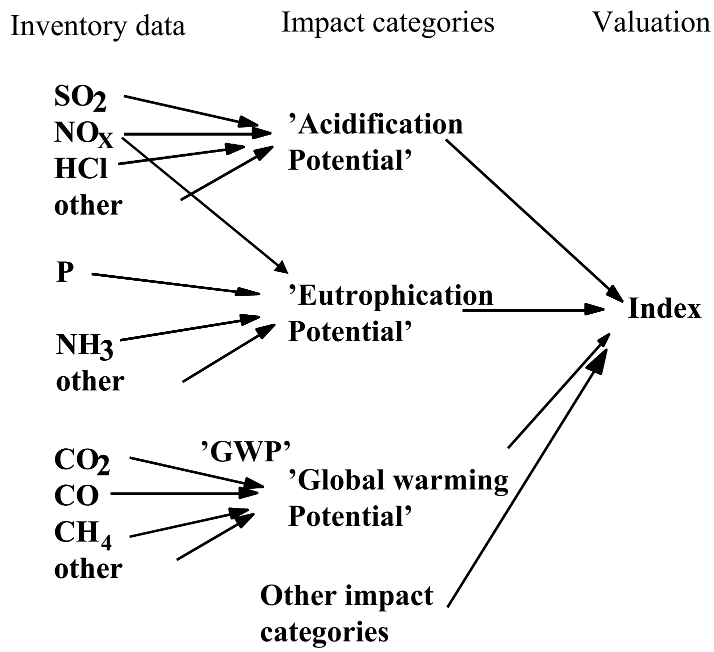


Figure 2.13 The LCA procedure where environmental stressors are inventoried and quantified and then interpreted and clustered to environmental impacts that finally can be valuated and aggregated to a single value.

Several different LCA models, referring to item iii. above, are publicly available. Examples with wider use are the *Environmental Theme Method* (Hejungs et al., 1992), *Ecoscarcity* (Ahbe et al 1990) and the *EPS, Environmental Accounting Method* (Steen and Ryding, 1992). The EPS method transforms the readings on the impact categories to a common currency called Environmental Load Unit, 'ELU', which is an environmental equivalent to the European Currency Unit – 'ECU'. The ELU-value is based on relative willingness of society to pay to safeguard a specific environmental quality, such as sustained ecosystems or clean air. For the practitioner there are commercially available LCI and LCA tools, often including generic environmental data concerning transports and materials.

To illustrate the LCA procedure the following example is given: Sweden has defined a list of 15 *environmental quality objectives* (SGB, 1997). From these objectives a number of *impact categories* such as: *Acidification* and *eutrophication,* are derived. The burning of fuels leads to emission of NO_x, which is an environmental stressor that affects these impact categories. LCA links the amount of NO_x from the specific product or process studied, determined by the inventory, to the effect on the impact categories and thus to the environmental quality objective.

The Swedish Institute for Transport and Communications Analysis (SIKA, 2002) has estimated the costs expressed in money per kg emitted to air for selected polluting gases to reach the national environmental objectives. See Table 2.3. The figures can be compared with for instance the preliminary rate for the CO_2 emission exchange, relating to the Kyoto agreement, of 0,008 Euro/kg, and with other weighting indexes. 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 in this system. The planning of roads and bridges can thus be based on the integrated cost of air pollution, investment, maintenance of infrastructure, accidents and travel time.

In Table 2.3 the ranking of a limited selection of environmental stressors according to three different weighting models is compared.

Table 2.3 Weighting indexes for some example emissions to air and for energy use as resource, according to different environmental burden weighting systems

System	Unit	Emission to air (kg)			Energy use (MJ)	
		CO_2	NO_x	SO_2	Fossil	Electricity
SIKA*	Euro	0,088	6,8	2,3		
EPS**	ELU	0,108	2,1	3,3	0,0094	0,0009
ET***	-	36,5	3970	3770	2,94	2,78

** SIKA (2002:1, 2). Estimated cost to reach national emission reduction objective. This model is only dealing with emissions to air why the energy resource is not taken into account.*
*** EPS 2000. (Steen, 1999)*
**** Environmental theme. Long view (Baumann and Tillmann, 2004)*

For the application dealt with in this research project, Swedish residential buildings, EPS 2000 was selected because:

- A monetary unit allows the addition of economical and environmental cost.
- It is easy for the practitioner to relate to a monetary unit.
- EPS 2000 is also a Swedish system, which is deemed advantageous at least with regard to local environmental aspects.
- It is not only related to air pollution, as SIKA, but also to energy as a resource, which is important for the perspective of the built environment, as long as energy is not abundantly available. The resource load of different energy sources is differentiated in EPS 2000, so that fossil, electrical and renewable energy give different environmental impact.

2.5.3 LCA - results, their interpretation and validity

The inventory step, LCI, is strictly quantitative and is not subject to any valuation. The difficulties here lie in the definition of the scope of the study, the allocation of environmental burdens, the cut-off criteria and the quality of the data. *Cut-off criteria* is the term used to define how far a LCI is reaching, from the particular product or process studied. For example, if the environmental burdens released by extraction of an energy source, used in a process, are taken into account. An allocation problem is, if by use of a waste material, this should be regarded as free from environmental burden or if a part of its environmental burden in the earlier life cycle, should fall on the waste material, and thus be transferred to the new product. Another allocation problem is how to distribute the environmental load if more than one type of product, are manufactured by the same process.

Quite often, LCA results are presented as a rating with regard to each impact category individually, such as acidification potential, global warming potential and so on. The normalisation and aggregation step is thus left out. For many applications, for instance, by improvement of a product or process, this information is often sufficient to support decisions. Going from LCI results to impact potential the quantitative inventory data have been subject to a characterisation based on environmental chemistry, toxicology, ecology etc. The complexity of this field has led to different alternative models, and international work is going on to establish common and complete characterisation models (Baumann and Tillmann, 2004).

In the next step, the valuation, the different results on individual impact categories are put together to a total environmental impact value. Compared to the impact category results it is even more difficult to assert such a value, as here also the relationships between the different impact categories is taken into account, and political considerations are included. The examples of weighting indexes in Table 2.3, indicate how different the environmental impact of a selection of stressors can be interpreted by various weighting systems. The relation between CO_2 and NO_x are here 1:77, 1:19, 1:108 respectively.

The result of LCA can thus be, either an aggregated value expressed in a specific impact unit, or a socio-economic cost, which is illustrated by Table 2.3, or a profile with regard to the set of impact categories. The use of the impact category profile is closer to the scientific fact, while the weighting indexes give a complete assessment. The choice of method must be considered for the particular application. One strategy is to apply two or more weighting models on the same inventory data to determine how robust the results are.

The advantage of using a monetary measure on the environmental burden is obvious. Environmental and economical costs can be directly added and the unit is easy to understand for the practitioner. However, there are two complicating aspects, which must be taken into account by the analysis:

- The discount rate for economical and environmental costs normally differs, as has been pointed out earlier. A future economical event is less important than the same event today, while a future environmental impact may be considered as serious as it is today.
- A certain part of the environmental cost may already have been included in the cost as an environmental tax, for instance, on fuels. Thus, it may be accounted for twice.

2.5.4 Application and experience of LCA in the building sector.

A large number of LCA studies regarding building products and systems, and also regarding entire buildings, have been undertaken. Reviewing these there are many critical aspects to consider such as cut-off criteria, allocation, data quality and weighting methods. The functional equality, which is extremely important when making a comparison, is often difficult to overview.

These issues can usually be treated adequately when working with the application of LCA internally in an organisation for product or process improvement. However, when comparing building products of different character, for example, steel, concrete and timber structures, any conclusion must be very carefully judged, and the requirements on transparency with regard aspects listed above are very high. The reliability and credibility of LCA is therefore sometimes questioned. Andersson (1998) shows the risks of disinformation, by examining four different LCA studies of competing materials, initiated by sewage pipes producing companies. The results and conclusions diverged greatly, which indicates that great care is needed when ranking the environmental burden of significantly different products. This problem will decrease when reliable and standardised environmental data for building products will be available. However, the problem to establish functional equality will remain.

Environmental data to support LCA and other purposes are gathered in *Environmental Product Declarations, EPDs,* which are described in the family of ISO 14000 standards. Type III EPDs, (third party assessed declarations according to ISO 14025) are normally based on a LCI, likewise are type II declarations (self-declarations according to ISO 14021). 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. Work to establish life-cycle inventory databases are reported by Häkkinen (2003) and from international standardisation organisations (Lindfors et al 2004).

Engineering tools for environmental assessment of alternative designs of whole buildings are, however, available. Sets of environmental data for different materials and components are then normally offered together with the programmes. Abu Sa'deh and Luscuere (2000) reviewed applicability and assessment methodology of 17 different commercially available tools. One example of such a tool is the Dutch 'Eco-Quantum' (Kortman et al 1998). Eco-Quantum utilizes the generic LCA programme Sima Pro (Pre Consultants, 1997) and a Dutch environmental performance standard. It offers one simplified assessment method 'Eco-Quantum Domestic' for planning of residential buildings with a limited set of alternative designs and a more general in-depth method 'EQ-Research' that enables the analysis of an arbitrary building, in different scenarios. The result is presented as four indicators: Exhaustion of resources, emissions, energy and waste. The Canadian 'Athena' model is another whole building life cycle assessment tool (Meil and Trusty, 2000), that provides a weighted profile of each design alternative constituted by embodied energy, global warming potential, air toxicity, water toxicity, resource use and solid waste.

Erlandsson (2004) has extended LCA with the context of product performance in a system for 'Sustainable Consumption Evaluation' directed towards buildings. This includes an environmental classification system that can be utilised as design criteria. Three classes are established: A, 'Sustainable', B, 'Environmentally sound' and C 'Acceptable'. This classified performance is linked to environmental impact, covering global warming, eutrophication etc., cf. Section 2.5.2. Erlandsson and Carlsson (2004), has further exploited this work in a guideline for environmentally oriented design and procurement of buildings. This document includes quantifications of the classes mentioned above with regard to for instance energy use, indoor climate health aspects, water, sewage and waste disposal. In Carlsson et al (2004) the system is extended to include indoor climate comfort.

Further to the quantitative LCA methods there are a number of simplified environmental evaluation procedures and classifications based on rough indicators. These are, however, normally founded on some kind of LCA. IfBE (1998) has, for instance, marketed an environmental database for building components that have been classified according to environmental life cycle as well as risk criteria.

2.6 Optimisation aids

2.6.1 From client needs to technical requirements

The first step of the design process is the definition of the requirements on the building. 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 and has been successfully applied in the manufacturing industry since the early 1980s. QFD can also be referred to as 'customer oriented product development' (Ryding, 1995). Akao (1992) defines QFD as a method for (I) developing a design quality aimed at satisfying the customer and (II) translating the customers' 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:

i. Client requirements and needs.
ii. Product characteristics that are required to match i).
iii. The relation between i) and ii).
iv. Results from an analysis performed regarding alternative solutions.
v. Opposition between characteristics.
vi. Target values for the required characteristics.

QFD is applied regularly in the manufacturing industry, and there are many examples of products that have been developed with this method. In the building sector QFD has been tried by the design 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 burden.

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. The authors present a procedure for characterization of requirements to be used from early project phases. Six first level themes are defined; functionality, environmental burden, resource use, life cycle cost, indoor quality and architecture. Each theme is broken down into a few different sub requirements. The QFD method is applied to combine requirements with relevant properties and to establish the relative importance of each aspect, by weighting factors and votes for further analysis to determine the functional specifications of the building.

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 material or 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. Examples from successful application of QFD from other sectors, however, show its potential to link the client needs to product design. The challenge is both to adapt the QFD-concept to the needs of the building sector and to use it for the relevant purpose.

2.6.2 Ranking of alternatives

A tool to rank different alternatives systematically is MADA - Multiple Attribute Decision Analysis (ASTM, 1998). MADA is an analytical hierarchy process that enables the calculation of one single measure of desirability for alternatives with several attributes measured quantitatively or qualitatively. 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. Compare example in Section 5.14. 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 computations 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 for the development of entire building concepts, while in the design of ordinary buildings, simplified ways of use are more appropriate.

2.7 Examples of practical applications of ILCD

Saari (2001) presents a pilot study on the design of a university building in Helsinki where a control procedure addressing both life cycle cost and environmental burden is applied. A weighting scheme is used including life cycle cost and four different environmental impacts: Use of non-renewable materials, global warming, acidification and formation of photo-oxidants.

Persson (2001) describes a test application on a residential building project, where a 3-dimensional product model in a commercial architects design programme was utilised for quantity surveying. The material and component quantities were transferred to a programme for building economical analysis, 'SYRE', developed at the department for Building Economics at Lund University. Furthermore, a database for environmental data on building products that was commercially available (IfBE, 1998), was included to permit combined environmental and economical assessment. The author concludes that the practicalities to integrate the economical and environmental assessment with the product model worked out well, but that the available environmental data was insufficient.

Sarja et al (2003) applied ILCD methods to develop a 'building concept', which would allow individually designed dwelling and office buildings, that were optimised in relation to lifetime quality. Performance properties of the building where systemised and classified including health and comfort, economy and ecology. Design principles and process descriptions were defined and examples of complete building concepts were elaborated and presented. One result from this work was that it is economical to increase energy efficiency substantially in relation to current practice.

Zeiler (2004) reports on the successful test of the methodology described in Section 2.2, in a pilot office building project in Holland, were also the Open build modular approach was applied, cf. Section 3.3.6.

In the manufacturing industry holistic product development is more common and the supporting tools presented in this chapter; LCC, LCA, QFD and Multi-Attribute Decision Analysis have been frequently and successfully used for a long time (Ryding 1995, Nilsson 1990). Baumann (1998) examined the use of LCA in the manufacturing industry, in 1995 in Sweden and Finland, and found that 37% of the Swedish companies in the manufacturing industry applied LCA, for product development. For all Swedish companies the figure was 12%.

2.8 Drawbacks and imperfections in present ILCD applications

At present, to the knowledge of the author, examples of the practical use of complete ILCD in the house-building sector are few. Typically ILCD is undertaken as a stand-alone pilot activity to test and illustrate theoretical models, and is not incorporated in the ordinary design work. This means that the threshold due to lack of accessibility of models, computing tools and life cycle data for the practical introduction of ILCD for the house-building application, is high.

The systems and models reported are typically decision support, or requirement management concepts, that do not include any tools for quantitative assessments such as LCC and LCA.

Redundant criteria and performance measurements occur. For instance, when aggregating economical and environmental accounting it must be kept in mind that a part of the energy cost or cost for disposal of waste often already reflect environmental consideration, by the way of an environmental tax.

For environmental assessment there is a general difficulty in the lack of general consensus with regard to the valuation of the different environmental stressors. For the specific application of comparing entire design alternatives of buildings there is furthermore a difficulty with regard to the access to reliable environmental data on building products and materials. This is particularly critical when comparing alternatives that are of significantly different origin.

2.9 Conclusion on current status of the ILCD methodology

The theoretical base for ILCD is clearly outlined and systemised within the framework of 'Integrated Life-time Engineering'. The different methods, tools and data called upon to support ILCD, are with few exceptions, available.

The application systems that have been developed for buildings are very comprehensive and typically organised as management systems. The link to the quantitative tools and data is however not so well developed why the introduction in practise is still waiting to come. The examples known to the author are typically demonstration projects and furthermore often specifically focused on environment.

Holistic life cycle consideration by design of buildings can contribute to a large positive impact on society in terms of sustainable development, and for the client in terms of lifetime quality and cost effectiveness of buildings. Research work in the construction sector in this direction has been going on since the beginning of the 90's and Integrated Life Cycle Design, ILCD, is a methodology envisaged to this end. Methods and data covering the different fields of ILCD are, with some exceptions, available and several systems to manage the design process accordingly have been developed and are to some extent used in practise. These are service life design, LCC and LCA.

3 BASE FOR THE APPLICATION AND DEVELOPMENT OF A TOOLBOX FOR INTEGRATED LIFE CYCLE DESIGN

In this chapter the author interprets the general principles and different elements of *Integrated Life Cycle Design*, 'ILCD', according to Chapter 2. The aim is to prepare a base for the introduction of lifetime quality optimisation, in practise, for the specific application addressed in this thesis: Design of Swedish multi-dwelling buildings with focus on the structural frame. The chapter outlines the hypotheses and research questions addressed in the thesis.

3.1 The concept of integrated life cycle design

Outline and design are the first activities in the lifetime of a building. ILCD is thus the starting point of lifetime engineering as discussed in Section 2.1. ILCD reinforces traditional design with tools to define and organise the needs of the client, predict life cycle performance of alternative technical solutions, and to rank their suitability with regard to the specific requirements. ILCD is a systematic way for the client to clarify the overall lifetime consequences for a limited number of alternatives. However, the client arbitrarily determines the relative emphasis put on each requirement, such as the importance of cost in relation to environmental burden or functional performance.

A building must satisfy a number of functional, economical and environmental requirements. One research goal is to compile a set of fundamental lifetime quality characteristics or attributes. Another research goal is to define relevant ILCD criteria for the appointed attributes. In Chapter 4, these two goals are addressed and in Figure 3.2 the resulting set of attributes is presented. These attributes form the basis for the requirements that are put on the building. Some attributes can easily be specified quantitatively, while others must be addressed more or less qualitatively. It is practical to express attributes in performance classes. Attributes can consist of a number of sub-attributes. Acoustics and thermal comfort are sub-attributes to indoor environment.

In order to satisfy the functional attributes, over the intended period of time, economical and environmental costs occur. These are in principle 'expenses' dependent primarily on the level of performance, but also on the design teams skill in meeting the expectations of the client in an efficient way. Compare Figure 3.1. In practice the expenses can also be targeted in line with other attributes. For instance a design criteria could be that the life cycle cost, or the construction cost, should not exceed xx Euro/m^2.

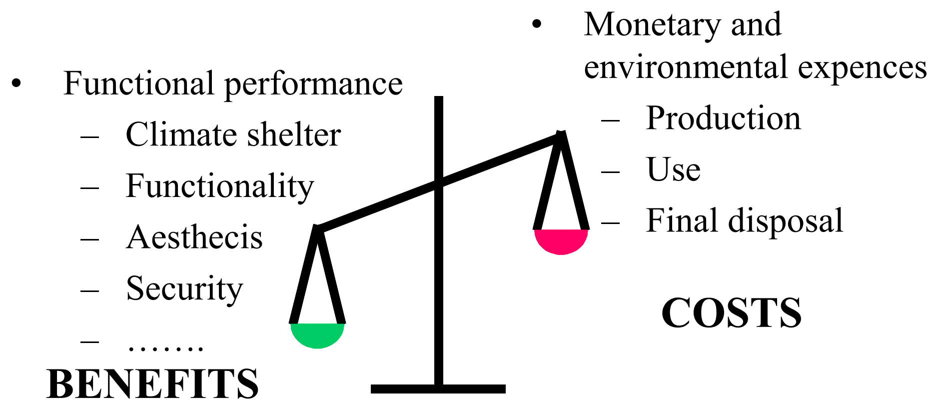


Figure 3.1 The principle of Integrated Life Cycle design: To balance benefits (functional performance and revenues) and cost (economical and environmental burden) over the life cycle.

The intended lifetime for residential houses, offices and public buildings is with few exceptions long compared to most other man-made objects. Furthermore, attributes often interact and are sometimes contradictory. For instance, lowering temperatures and decreasing ventilation reduces energy demand but is in conflict with indoor climate. Design of the building, therefore, need to be based on a holistic life-cycle perspective, which is the core objective of ILCD. There are also dilemmas from an organisational point of view, such as how to deal with an increased cost for the first client that will provide benefits for later client's, 20 or 40 years ahead in time.

Integrated Life Cycle Design is a combination of two different principles:

- <u>Integration,</u> which implies that different attributes 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 in Section 4.13.
- <u>Life cycle,</u> meaning that the design should take costs and environmental burden of production, use and final disposal into consideration. See Figure 3.2. Life cycle can be defined in different ways, cf. Figure 2.8.

Looking at Figure 3.2 it is apparent that aspects to some extent are redundant, such as energy use in relation to life cycle cost and environmental burden. This is further discussed in Section 3.3.2.

	⇐ Life Cycle Design ⇒		
	Production	Use	Final disposal
⇐ Integrated Design ⇒		Mechanical resistance and stability	
		Safety in case of fire	
		Indoor environment	
		Safety in use	
		Acoustics	
		Energy use	
		Durability	
		Robustness and risks	
		Life time usability	
		Architecture	
		Life cycle costs	
		Environmental burden	

Figure 3.2 Integrated life cycle design approach. Fundamental attributes defined in Chapter 4 and their primary relevance to specific life cycle phases [grey bars].

3.2 Calculation horizon and end of life scenario

One principal question by life cycle appraisal is how the calculation horizon may affect the result. If the aim of the calculation is to establish a representative long-term cost profile, the question is: When is a stable relation between initial and operating costs is achieved? If the aim is to assess alternative designs, the question is: How does the selected calculation horizon affect the relation between the alternatives?

Bejrum, cf. Figure 2.8, prefers to use the total life of the building from construction to demolition. Multi-dwelling buildings, however, normally last for time span of 100 to 200 years, cf. Section 1.1, and the sense in trying to assess the entire life cycle into a rather diffuse distant future can be argued. For a strictly economical calculation it is deemed sufficient to apply a calculation horizon, which is fulfilling the aims discussed above. For an environmental consideration, with regard to, for instance, final disposal or the energy use during operation, this simplification may not be valid. Compare the distinction between discount rates between economical and environmental, discussed in the beginning of Section 2.3. In Section 5.11.3 this question is addressed.

A second principal question is how the end of life scenario affects the results of the life cycle appraisal. The end to the life for a building may induce, either a cost referring to the demolition and final disposal, or a gain in terms of a second-hand value. It may be difficult to predict this at the design phase. In Section 5.11.4 the impact of the end of life scenario is studied.

3.3 The process of integrated life cycle design

This section deals with the elements of ILCD following the outline by Sarja (2002, p 11), who separates this methodology into the following phases:
1 Investment planning
2 Analysis of client's and users needs
3 Functional specifications of the building
4 Technical performance specifications of the building
5 Creation and outlining of alternative structural solutions
6 Modular life cycle planning and service life optimisation of each alternative
7 Multiple criteria ranking and selection between alternative solutions and products
8 Detailed design of the selected solution

The success and efficiency of each phase, and thus the entire process, is dependent on the quality of work at the preceding phase and also on the ability to convey information between phases, both forwards and backwards, in the process. Therefore, a final process step for feedback is added to the list above. For a repeat order client the initial phases may to various extents be covered by a general company related market or product analysis, leaving only limited parts to be dealt with for the specific project.

In principle, the construction process is linear, starting at the point where the client perceives that a building is required, and ending when the client moves into the house. Then, the facility management process starts. Contrary to construction, this is a continuous process, normally without any predefined end, in the residential building case.

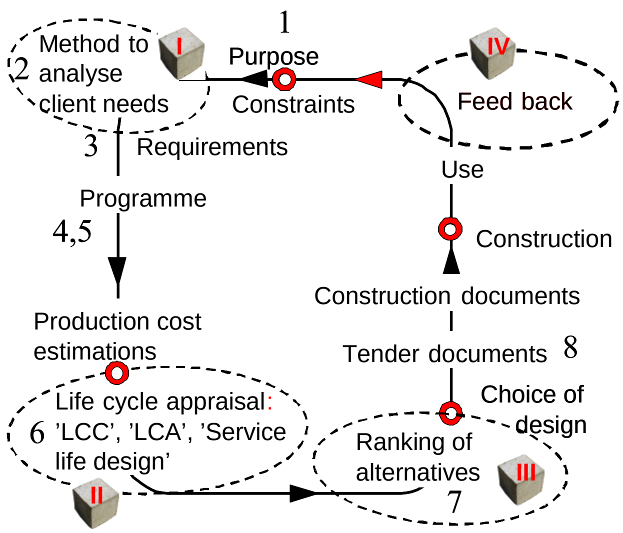
From the perspective of a repeat order client, such as a housing company, however, the processes can be combined in a cyclic model. Changing needs on the market, and an ageing stock from time to time, trigger the need for production of new buildings. Experience from the operation of other buildings and earlier productions can and should be utilised in the design of a new building. This is crucial to obtain continuous improvement. Therefore, the elements of ILCD are illustrated as cornerstones of a cyclic process, see Figure 3.3. This model is the base for the methodology developed in this work.

For cornerstone I the method described in Section 2.6.1 is proposed. Cornerstones II and III are dealt with in spread sheet models and described further in Chapter 5. For cornerstone IV a qualitative method has been tested and is described in Section 5.15.

I Analysis of client needs. Short- and long-term needs are systematically defined, analysed and prioritised.

II Life cycle appraisal. Economical and environmental life cycle appraisal to quantify life cycle consequences of alternative designs

III Ranking methods. Multiple Attribute Decision Analyses is employed to aid the choice of design with regard to several different aspects.



IV Feed back. Information from production and facilities management of the building is systematically recycled to the design team and management

Figure 3.3 The cornerstones of the integrated life cycle design methodology developed in this work. The Arabic numbers 1 to 8 indicate the position of the process steps in the ILCD process, defined by Sarja (2002).

Likewise the traditional design process, ILCD operates from the general to the specific, that is, from rough sketches in the early phases to the detailed construction documents. The whole life appraisal tools must be adapted accordingly in order to be practicable. At the initial phases only the most crucial aspects are dealt with, while later on in the process the information is being step by step refined.

3.3.1 Investment planning

At this first stage of the design process the economical and technical framework of the building project is defined. Areas, types of spaces, service life and objectives in terms of economy, environment, architecture and flexibility are considered and decided, guided by a market analysis. Table 3.1 shows an example of market analysis applied by a housing company.

Table 3.1 Market analysis used by a housing company

Category	Base	Medium	Exclusive
Aesthetics	Plain	Medium	High
Technology	Repetitive. High prefabrication	Prefabricated or build on site	One-off. Built on site
Location	C, B-	B-, B, B+	B+, A
Customizing	Norm level	Medium	High
Rent (€/m^2, year)	110-120	120-145	145-175
Site conditions	Simple	Simple-Medium	No restriction
Trade mark – profile	High	High	Low
Environmental burden	Low	Medium	No restriction

Based on the specific objectives and knowledge about which are the decisive parameters with regard to life cycle performance, initial assessments of a limited selection of strategic technical alternatives can be undertaken. Type of building frame, façade, ventilation system, window areas, orientation of building and level of prefabrication are some choices that will have major impact on the long term performance and the production of the building.

At this initial design phase the life cycle economy and environmental burden of the selected alternatives must be evaluated in a simplified way. The focus should be set on critical items, and on items that are affected by the design choices. Thus, the life cycle appraisal tools can become effective. One research question is to define the most significant aspects with regard to life cycle costs and environmental burdens. Furthermore, the aspects that are reasonably dependent on the design of the building should be picked out.

The deliverable of the investment-planning phase should be an adequate decision base to stop or continue the project, and a limited number of principal design alternatives to carry on to the next design stage. Furthermore, a time framework should have been established, including time for completion and a target service life, including considerations of possible future changes in use.

3.3.2 Analysis of client's and user's need

There are a great number of different requirements and needs that must be addressed. Some of these requirements interact. They can be supportive but also contradictory. Buildings represent a large investment in monetary but also in natural resources. They are normally intended to last for a long time, so the time perspective must also be considered, which implies changes in the requirements are likely to occur during the lifecycle. A predefined set of design criteria linked to relevant functional quality levels and design methods, which conform to current practice facilitates this step.

As remarked by Figure 3.2 attributes can to some extent be redundant, such as energy use in relation to life cycle cost and global environment. Environmental taxes on fuels are normally included in the LCC calculation and may thus be accounted for twice, if also environmental burdens are specifically estimated and used as design criteria. This is difficult to avoid and must be kept in mind by the ranking of design alternatives. It is not deemed relevant to propose some general guideline on redundancy, as different clients and design situations may call upon different interpretations.

The first client's needs must be balanced against the generality and adaptability of the building. For the long-term owner with an extensive building stock, such as a large housing company, this issue is not controversial. However, as pointed out earlier, for a smaller entity such as a 'one house' building cooperative the question arises: Are the developer and the first generation of owners willing to accept a higher investment that will provide future benefits, such as low periodic maintenance costs or flexibility for changes? At least in theory, the added investment is reflected in a higher second hand value, which is one way to deal with this question also by life cycle appraisal.

One research question is to examine the economical and environmental life cycle consequences of alternative levels of functional quality.

To complicate the decisions, there are different stakeholders to satisfy. The client may have different priorities in relation to the society. This is apparent with regard to the aspects of environmental burden. The client may be inclined to avoid any added investment cost that improves environmental performance, if that cost is not balanced by any added economical return.

Besides these stakeholders there are a number of parties involved in construction and management of buildings supplying: materials, design services, construction work, project- and facilities management and so on. The suppliers normally have a primary interest to provide the expected quality of their product or service at the lowest possible cost.

Depending on the organisation of the building or maintenance process, in the specific case, there may be problems related to conflicts of interest between parties. Such organisational aspects are not dealt with in this work. However, it is plausible that the improved basis for decision, provided by ILCD, will also improve the collaboration between the actors involved.

The deliverable from the client need analysis is a refined and more detailed scheme of design objectives, in principle according to Table 3.1, including also detailed spatial demands. Furthermore, the relative importance of each objective should be determined, in order to clarify priorities for the following work. One research question is to establish a generic set of design criteria for residential buildings.

3.3.3 Functional specifications of the building

This phase is the synthesis and transformation of the client needs from the proceeding phase to functional specifications on the specific building. The term functional implies performance related requirements.

QFD as mentioned in Section 2.6.1 is often applied by product development in the manufacturing industry for this purpose. Based on the experience presented in Section 2.6.1 it is envisaged that QFD is suitable for the repeat order client or the producer of whole building systems, or components to establish and continuously elaborate design criteria for series of buildings. As a design tool for one specific normal multi-dwelling building project it is deemed to be complicated.

The deliverable from this stage is a list of relevant functional requirements with their particular importance indicated.

3.3.4 Technical performance specifications

Here technical performance criteria related to the functional specification are defined. Where it is possible, attributes should be specified quantitatively, or via classes or threshold values such as energy demand, fire safety or acoustic classes. Aspects such as adaptability, flexibility and social factors often need to be treated in qualitative terms. In Chapter 4 the ILCD criteria for the important attributes are discussed. Preferably the objectives should be possible to verify with available standard methods after completion of the building. The deliverable could in principle be organised as the criteria matrix outlined in Table 3.1, cf. Table 5.2.

3.3.5 Creation and outlining of alternative structural and service systems solutions

The alternatives outlined in the investment analysis are now further elaborated with the constraints and demands stated in the technical requirements, defined at the preceding stage.

The building is systemised into a number of functional modules, typically foundation, structural frame, external claddings, heating and ventilation systems. Depending of the type of building, and importance of each item, further segmentation could be applicable such as floor coverings, interior partitioning walls etc. Modularisation is the basis for life cycle planning and cost estimations.

The output of this stage is a number of sets of well-defined modules forming alternative designs of the building. Principal dimensions of components must be determined in order to allow, for instance, more exact cost calculations.

3.3.6 Modular life cycle planning and service life optimisation of each alternative

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. For multi-dwelling buildings this implies more than 100 years. Other components will be exchanged one or several times during the life cycle of the building, either because their technical service life is limited or because they become obsolete. Obsolescence is discussed in Section 4.9.

In order to optimise components and systems with regard of durability over the total building lifecycle and to facilitate changes a modular design approach is envisaged. Sarja (2002, p 17) discusses the classification of building modules into target life classes so that the components and systems can be optimised with regard to life cycle costs and environmental burden. In Figure 3.4, the principles for modular design with regard to target design lives are presented.

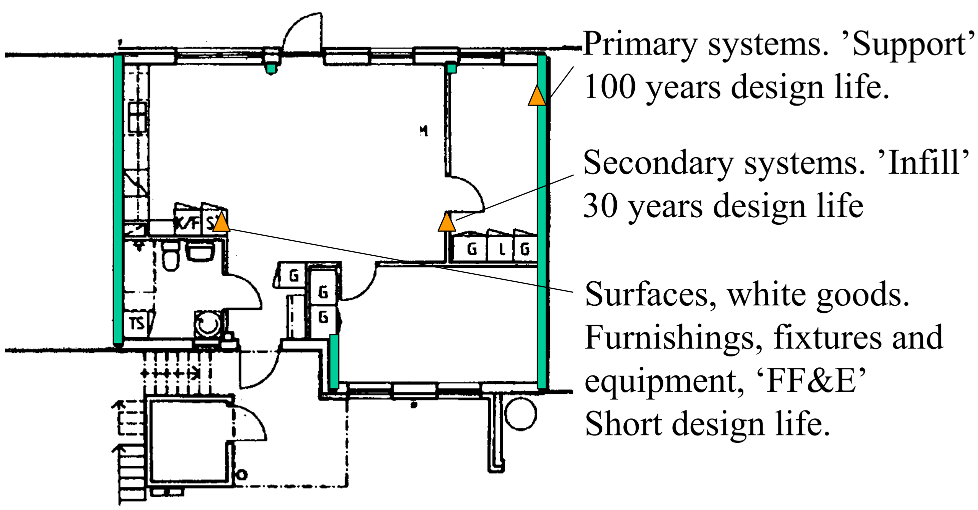


Figure 3.4 Plan of building with classification of components and systems in target life modules or levels defined by the 'Open Building approach'. Example from project Erlandsdal, Svedala.

A system for modular life cycle planning where the building is deconstructed into packages or 'levels' can be collected from the Open Building, 'OB' movement (Kendall, 2000). 'OB' is a strategy for design, production planning and facility management based on the physical organisation of buildings in layers. These extend from a top level of urban planning, to the building with its framework 'support', and fit-outs of components and systems, 'infill', and finally furnishings, fixtures and equipment, 'FF&E'. Key features of OB are design for flexibility 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).

Bejrum et al (1996) proposes that life cycle costing of buildings can be divided into three main categories: (1) Building, (2) system, and (3) component. Investment planning typically refers to the building level, and the aim is here to maximise the profit of investment over a selected calculation period. This implies that the revenues, typically the rent, also must be added to the LCC-calculation. Technically this is defined as a Life Cycle Profit, 'LCP'- calculation. Bejrum et al further states that the component level is addressed with LCC and system either with LCC or LCP. In this work LCC is used irrespective of planning level. Revenues could however in principle be added to reach the full LCP perspective.

A base for service life optimisation could be obtained by packaging the important maintenance and refurbishment measures in time, so that these major activities can be executed systematically, at recurring intervals. One research goal is to establish a generic modular service life plan for Swedish multi-dwelling buildings with major maintenance activities, replacements and length of lifecycles for components and the entire building clearly defined and co-ordinated.

Expected service lives for the different modules should be defined. Life cycle cost and environmental burdens should be estimated for the alternatives based on key factors such as periodic maintenance, energy use, service life and final disposal. Tools and information used are LCC and LCA. Further to the typical service life criteria mentioned above, this part of the ILCD should involve consideration of the flexibility and obsolescence aspect presented in Section 4.9. Major renovations are apt to be combined with changes in use of the building, or reconfiguration of flats.

From the technical service life point of view the periodic maintenance strategy can be to provide constant technical standard. An alternative mode, 'run down', is to operate with the lowest possible periodic maintenance until a predefined end of the life cycle. The first alternative is deemed to be dominant by management of multi-dwelling buildings, and it is thus used by the different calculations in this work. The methods that are developed are, however, fully open for the application of alternative periodic maintenance regimes.

The framework, *support*, should be general, as it will remain throughout the lifetime of the building, while the *infill* can be adapted according to the user. In Figure 3.5 some principal 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. A material that is suitable for the primary system may be less fit in a secondary system position. Concrete structures are typically found in the primary system.

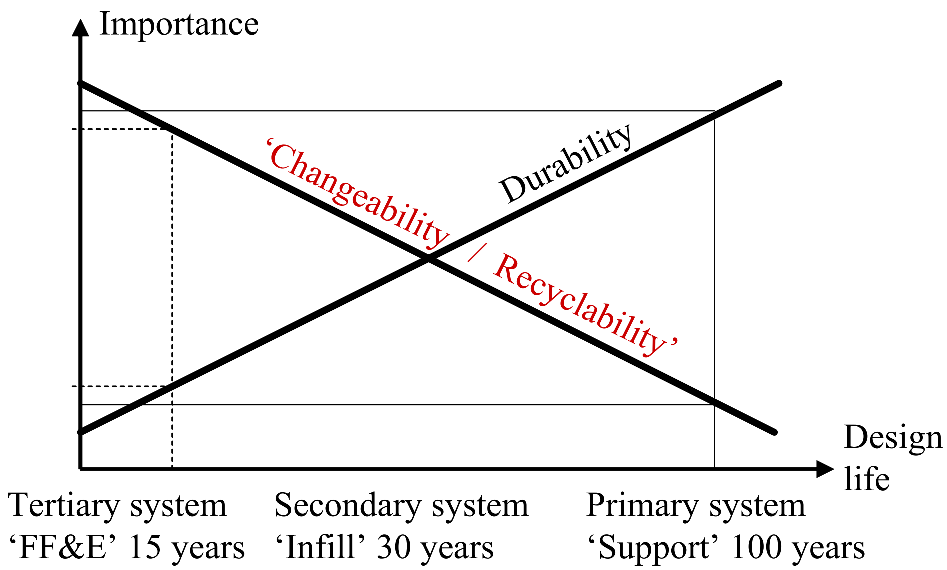


Figure 3.5 Implications of design life on importance of durability and aptitude for change or recycling, which should be considered by whole life appraisal

The physical separation of systems with different service lives, and the accessibility of components that need servicing or replacement, are conceivable with the modular approach.

An example of how life cycle usability might be more or less facilitated is presented in Figure 3.6. Here, the electrical service installations in two, basically identical buildings, taken from the field study on life cycle costs, are shown (Johansson and Öberg, 2001). 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 where optimised to go the shortest way. It is rather obvious what solution would be the easiest to maintain, change, and in the end, recycle. Note that there is no reason why, in the cast in place building, the installations should not be organised in the similar systematic way, as in the prefabricated building.

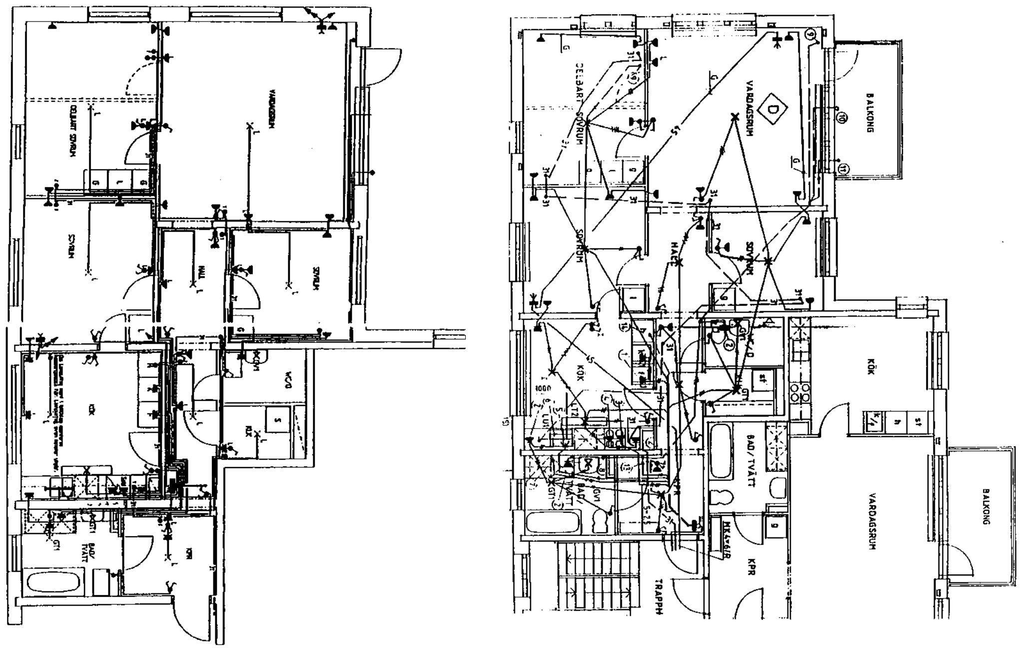


Figure 3.6 Alternative solutions regarding electrical installations for the same project (Paus, 1996).

The result of the modular life cycle planning is a limited number of complete building alternatives, each formed by consistent structures and systems fulfilling the technical performance specification. The economical and environmental life cycle consequences for the alternatives are furthermore quantified.

3.3.7 Multiple criteria ranking and selection between alternative solutions and products

At this point the designs are compared and the most suitable building alternative is selected, based on some deliberate balance of benefit and cost. The decision criteria could be for instance (Sarja, 2000):

i. Best in all requirements.
ii. Best weighted properties with reasonable cost level.
iii. Best in preferred requirements, fulfilling accepted levels in all other requirements.
iv. Best in valuated multiple criteria benefit/cost ratio.

Other steering strategies could be:

v. Lowest life cycle cost, fulfilling accepted levels in all requirements.
vi. Lowest environmental burden over the life cycle, fulfilling accepted levels in all requirements.
vii. Lowest investment cost, fulfilling accepted levels in all requirements.

A tool that can be used for more advanced ranking and optimisation, such as iv) above, is Multiple Attribute Decision Analysis (ASTM, 1998). MADA enables the calculation of one single measure of desirability for alternatives with several attributes measured quantitatively and qualitatively, see Section 2.6.2 and application examples in Sections 6.8, 7.3, 7.7 and 7.9.

3.3.8 Detailed design of the selected solution

The traditional tools are applied for each design discipline. However, the technical specification in the ILCD process may have highlighted some aspects that need increased attention compared to current practice, such as durability requirements, flexibility for future changes, or indoor climate comfort.

3.3.9 Feed back

In order to obtain continuous improvement of buildings, feedback of experience from production and operation should be given to the design team. This is deemed to be of fundamental importance and has thus been assigned a specific part in the ILCD process.

3.4 Summary – research questions

The following research questions were defined in order to address the aim and research tasks outlined in Chapter 1:

- To map the fundamental lifetime quality characteristics (attributes) for Swedish multi-dwelling buildings.
- To establish relevant ILCD criteria for the attributes.
- To define different functional quality levels for the attributes, and to outline assessment methods. Where it is possible, attributes should be specified quantitatively, or via classes or threshold values, such as energy demand in kWh/m^2 or acoustic classes.
- To clarify the most significant aspects with regard to life cycle costs and environmental burdens for dwelling buildings.
- To compile a toolbox for simplified ILCD that fits reasonably into the current design practice.
- To examine the economical and environmental life cycle consequences of alternative levels of functional quality.
- To establish a relevant time horizon for life cycle appraisal of multi-dwelling buildings.
- To examine the significance of the end of life scenario, on the result, by life cycle predictions.
- To establish a generic modular service life plan for Swedish multi-dwelling buildings with major maintenance activities, replacements and length of lifecycles for components, and the entire building, clearly defined and co-ordinated.

4 THE ATTRIBUTES OF RESIDENTIAL BUILDINGS

For the practical application of ILCD, the generic fields of requirements on buildings, cf. Section 2.2, must be transferred to specific design criteria, relevant for the particular project. The collected properties, or performance, of the finished building will respond to the design criteria that are put on it. This chapter reviews and defines the important properties, here referred to as attributes, of multi-dwelling buildings.

The attributes are more or less related to the design of the structural frame, which is the focus of this work. This is commented on where relevant.

The following review of attributes is primarily based on studies of literature, current practice and field surveys. Contributions by the author are clearly marked. The chapter is organised with one section for each attribute, including:

- A general description of the attribute.
- A discussion on how concrete relates to the attribute.
- A review of the attribute in the ILCD perspective with and, if relevant an outline of ILCD criteria. Design tools are discussed in Chapter 5.

To safeguard the direct public interest in building products, and thus buildings, the EU Construction Product Directive (EU, 1988) specifies 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 (7)* requirement follows automatically as it is stated that the requirements must: ‘subject to normal maintenance, be satisfied for an economically reasonable working life’.

Referring to the state of the art review in Chapter 2 the following additional attributes that were deemed to be of fundamental importance by the author:

Robustness (8). Robustness indicates the capability of the building to withstand any more or less expected incident or condition. Robustness is relevant both with regard to the construction and the user phase. It is linked to mechanical characteristics and durability of individual components and materials. Robustness is, however, also an integral design issue, dependent on the interaction between components and systems. Finally, the technical detailing or concept is crucial. A flat roof is in principle less robust than an inclined roof with regard to water leakage. Robustness is therefore here defined as a specific, risk related, attribute.

Lifetime usability (9). This attribute defines how the building structure and service systems are adapted or adaptable to the needs of the client at present as well as in the future. This reflects the risk for obsolescence, cf. Figure 2.9.

Architecture (10). Architecture covers the field of important factors that determines how a building is conceived by the user, in terms of well-being and usability. Architecture thus strongly influences how a building can be sustained over time. Character, image, provisions of security, confinement, correlation to ambient and local heritage are examples of the many aspects that are involved. Some of these can be addressed quantitatively and some only qualitatively.

Life cycle costs (11) and environmental burdens (12) are rather obvious characteristics that depend on the intended functional performance level, and the ability of the building to live up to the requirements, over the lifecycle. The impact on nature is in this work conceived as an environmental cost. In the design situation, the costs can be viewed either as a consequence that should be minimized, or be targeted and treated as any other functional design criteria. The relation between benefit and cost was further discussed in Section 3.1, cf. Figure 3.1.

Some attributes, typically those related to safety and health are guaranteed by minimum requirements stated in building regulations. Such requirements are sometimes referred to as *screening* criteria, indicating that they are unconditional. These minimum levels can therefore not be subject to any integrated life cycle design optimisation. However, it may be of interest for a client to select a higher quality than the screening level. This is commented on in relevant cases.

It is not pleaded that this set of 12 fundamental attributes, is the complete and optimal way to systemise the requirements on buildings. It is acknowledged that they contain partially redundant criteria, for instance, with regard to energy use and environmental burden. Furthermore aspects such as mechanical resistance, durability, lifetime usability and robustness cannot always be distinctly separated. However, ILCD in general, and the toolbox developed in this thesis is fully open to add, remove or change any of the attributes, according to specific needs and priorities of the client.

4.1 Mechanical resistance. Essential Requirement no 1

Minimum requirements on mechanical resistance and stability are defined by building regulations. Permanent building structures are designed for:

i. The ultimate limit state, which refer to maximum load capacity, including also some accidental situations.
ii. The serviceability limit state, which is reached when a structure does not function due to deformations, cracks etc., induced by the long-term load.

The loads for the various limit states are differentiated by the system of partial safety factors, based on probability theory, given in CEN[8] (2001).

Concrete and mechanical behaviour
Mechanical behaviour of reinforced concrete structures is characterised by:

- A ductile stress behaviour, where failures are proceeded by substantial deformations and cracking.
- A low proportion of imposed load due to high the self-weight of concrete.

For a 250 mm concrete slab in a dwelling building designed according to the European structural 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 introduction of new openings for new stairways or shafts can thus normally be facilitated. In a two way reinforced slab, loads can often be redistributed without any specific measures and in slabs or beams that are pretensioned in one direction a large opening can be catered for using steel yokes to carry the cut slab, or by fiber composites glued to the concrete structure (Täljsten, 2002).

The high self-weight of concrete may also be a disadvantage. Typically lighter structural materials often have to be used, when an existing building is going to be extended with additional floors, if the building was not originally designed for the added load. In case the foundation conditions of a building are difficult, a higher total weight of the building increases the cost of the substructure.

In Annex 4. A the common types of frames for Swedish multi-dwelling buildings are presented, and in Table 4.1 normal spans for different floor slabs are displayed.

[8] European Committee for Standardization

Table 4.1 Normal thickness and spans for concrete slabs for dwelling buildings.

Type	Annex 4.A Type	Thickness (mm)	Normal span (m)	Reference
Prestressed hollow core slab	B, C	200	5-9	(BE, 2001a)
Prestressed hollow core slab	B, C	270	6-13	(BE, 2001a)
Floor slab	A	200-300	2-8	(BE, 2001a)
Pretensioned floor slab	A	200-300	5-11	(BE, 2001a)
Cast in place slab	A	200-300	3-10*	(SFF, 2000)
Cast in place slab, post tensioned	A	200-300	8-15*	(SFF, 2000)

** Dependent on support arrangement*

The decisive mechanical properties of reinforced concrete are concrete compressive strength, reinforcement tensile strength and the concrete modulus of elasticity. Also important are concrete tensile strength, creep behavior, shrinkage and occasionally the steel compressive strength. Peterson (2003) presents ongoing development with regard to material properties, such as high performance and self-compacting concrete and its implication on structural possibilities by house construction.

Integrated life cycle design criteria and mechanical resistance:
In terms of whole life optimisation the limit states are unconditional screening attributes with regard to mechanical resistance. 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 4.7 and 4.8.
The serviceability limit state provides further options. Deformations and vibrations can be adapted to the requirements of the client. Lagerqvist and Johansson (2004) describe three stiffness classes, defined as S1, S2 and S3. This aspect is relevant for lightweight structures and very tall buildings. Ordinary concrete dwelling buildings automatically qualifies for the highest performance class; S1.
ILCD criteria relating to mechanical resistance are:
* Load carrying reserves, which determines the possibilities for expansion and load changes, and thus the flexibility of the structure.
* Load carrying capacity in relation to cost and environmental burden.
* Deflections and vibrations, which effects usability and comfort.

4.2 Fire safety. Essential Requirement no 2

4.2.1 Fire related characteristics and classification of building

The fire resistance classification of building structures is, according to European standards, determined by: Load carrying capacity (Resistance) by fire ‘R’, integrity ’E’ and insulation ‘I’, followed by the time, in minutes, that the structure or component will withstand a standardised fire load, eg. R 120, EI 60 or REI 90.

Ignition properties of *building materials* are defined in a set of 'Euroclasses' ranging from A1 and A2 that are non combustible to F that ignites in less than 2 minutes at specified circumstances. Walls in multi-storey dwelling buildings are required Euroclass C, or better and roofs Euroclass B or better, implying ignition after more than 10 and 20 minutes, respectively. Fire escape areas such as staircases require Euroclass B or better on all surfaces.

The total quality of a *building* with regard to fire is determined by:

- Passive or inherent aspects in the building such as:
  - The ability to keep a fire in a confined area /EI/.
  - The fire resistance of load carrying and stabilising structures /R/.
  - The behaviour of the materials regarding ignition, combustibility and build-up of gases /Euroclasses/.
  - The escape possibilities.
  - The work environment for rescue teams.
  - The possibility to restore a building after a fire.
- Active aspects such as:
  - The fire alarm systems.
  - The availability of fire protection devices such as sprinklers. (Such systems are normally not used in Swedish residential buildings).
  - The equipment and access time of the fire fighters.

Karlsson and Östman (2000) have developed a method for integrated assessment of fire safety in buildings, in principle according to the list of factors above. The intention is to utilise the contribution of all relevant factors in the valuation of a design alternative. Each factor has an attached basic weight of relative importance. This is multiplied with an integer record from 1 to 5, representing the quality with regard to this factor. By adding the products of factor weight and its specific quality, an aggregated rating of the fire safety of the building is obtained.

There are three levels of fire safety in a building according to the Swedish building regulations BBR (Boverket, 1998). The highest safety level, Br 1, is applicable for three storey buildings and higher.

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 Br 1 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 R 60, R 90 or R 120 for residential buildings depending on the number of floors in the building and the type of structure.

4.2.2 Concrete and fire safety

Concrete is not combustible and is thus qualified for the highest ignition Euroclass: A1.

The fire design criterion of reinforced concrete is based on the temperature of the steel reinforcement and its particular mechanical stress level. The load capacity of steel at different temperatures is well defined. At between 250°C and 300°C, depending on type of steel, the reinforcement start losing strength significantly. The fire load and the thickness and thermal conductivity and heat capacity of the concrete cover govern the development of the steel temperature by fire exposure. Conductivity and heat capacity of concrete are dependent on moisture conditions and temperature.

Fire safety design of concrete structures for residential buildings can normally be performed by handbook methods such as BE (2001,b). Here slabs and walls as well as linear structures, such as beams and columns can be analysed.

Examples of concrete structures that satisfy the highest fire safety class, according to the Swedish classification, Br 1, requiring R 120 and EI 60: At 100% utilisation of the strength a 160 mm concrete slab with 32 mm distance from the centre of the reinforcement to the surface exposed to the fire or a 120 mm wall (BE 2001,b). With lower utilisation of strength, for instance 80%, the cover can be reduced by 5 mm and with pre-stressing reinforcement it should be increased by 5 mm.

For high-performance concrete, with moisture content above a critical level, the risk for explosive spalling of the concrete cover, and thus immediate exposure of the steel, must be considered. Plastic fibres in the concrete that melt by fire and thus allow expansion of heated moisture, can avoid this. Guidelines are given in the High Performance Concrete Structures Design Handbook (HPCSDH, 2000).

The load bearing, shielding and ignition properties of concrete imply that fire seldom is a decisive design criteria for concrete structures in dwelling buildings.

Integrated life cycle design criteria and fire safety:
In terms of whole life optimisation, fire safety is an unconditional screening attribute, safeguarded by a set of minimum requirements. However, a client may acquire an enhanced safety level.

4.3 Indoor climate – health, hygiene and comfort. Essential Requirement 3

This section is introduced by a brief general overview of indoor climate, followed by an examination of the two primary quality aspects: Temperature and air quality. Then quality indicators and assessment of indoor climate are reviewed, and finally concrete and indoor climate is discussed. Acoustics is dealt with in Section 4.5.

4.3.1 Introduction to indoor climate

It is generally acknowledged that comfort, health and mental capacity are related to the climate to which we are exposed. Since a large part of our time is spent at home and inside other buildings indoor climate is important to our well-being.

The indoor climate can be, partly but not fully, described and assessed in quantifiable terms. Predictions can be made regarding moisture conditions, operative temperature and air exchanges in relation to the ambient climate, materials, ventilation and air leaks in the climate shell. Figure 4.1 summarises the internal and external factors governing the indoor climate.

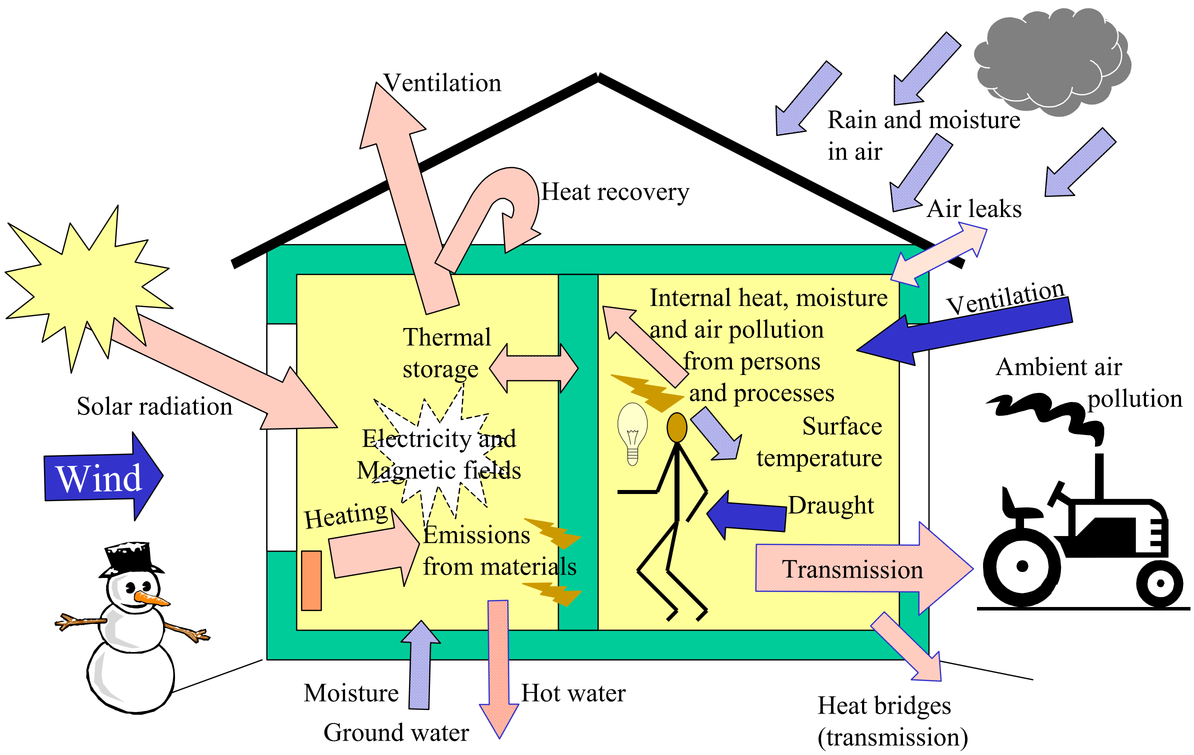


Figure 4.1 Overview of indoor climate and energy performance factors.

It is the response of the building to the internal and external factors and loads that determines the quality of the indoor climate. This response is both off an active nature, such as ventilation and heating, and of a passive nature, such as the properties and configuration of relevant materials, components and structures. Indoor climate is intimately related to energy aspects, cf. Section 4.6 and Figure 4.3. Furthermore, all factors displayed in Figure 4.1 are in principle interrelated. Therefore, indoor climate should be treated and designed in a holistic way.

The borderline between health and comfort aspects with regard to indoor climate is diffuse. For example, within certain intervals temperature is an issue of comfort but beyond a specific point it affects health. Wyon (1973) describes a topology of the thermal environment, displayed in Figure 4.2 stating that:

- There are several interacting parameters governing the human response (here depicted as A and B, which could represent air velocity and temperature, but in reality is often multi-dimensional).
- The range for survival, or health, is wider in comparison with the range for performance and comfort.
- Performance and comfort may or may not coincide or overlap.

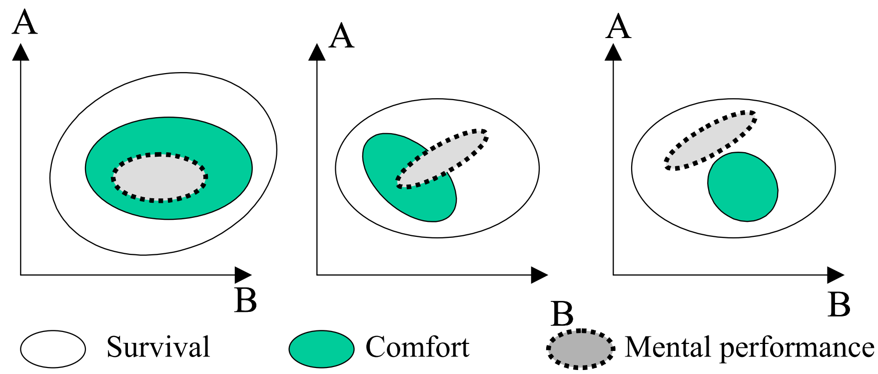


Figure 4.2 Topology of the thermal environment after Wyon (1973). Survival can be understood as a health criterion, with wider limits than the comfort or performance criteria with regard to the same indoor climate aspect.

This topology is valid also with regard to other aspects such as noise, particles, odours and chemical emissions. In terms of building requirements this principle can be interpreted such as that the survival or health range is a screening, minimum quality threshold value, normally stated by norms. The tighter comfort and performance ranges are optional higher quality levels that can be selected according to the client's demand. An example of this is given by Willis et al (1995), which describe the ventilation rates according to two functions:

- Health (Respiration, odour avoidance and pollutant removal) 0,5-1 airchanges/hour
- Comfort (Removal of heat produced by internal and solar gains) 1-5 airchanges/hour

4.3.2 Indoor climate quality aspects - Temperature

The perceived thermal comfort in a building depends on the operative temperature and the air humidity. The operative temperature defines the perceived temperature and is a function of temperatures of the air and on surfaces, and of the velocity of the air. In the Swedish building regulations BBR (Boverket, 1998), the minimum operative temperature is set at 18°C in residential spaces 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. Guidelines and classification with regard to thermal comfort are stated for instance by FISIAQ (1995) or by CEN (2004), see Table 4.2. Note that in the CEN draft standard the link to the acceptance of the inhabitants is presented.

Table 4.2 Thermal classification according to FISIAQ (1995) and CEN (2004).

Class	Temperature			Air velocity	
	Summer	Winter	Gradient	Summer	Winter
FISIAQ	Cº		K/m	m/s	
1	22-25	21-22	2	0,15	0,10
2	22-27	21-23	3	0,20	0,15
3	22-27	20-24	4	0,25	0,15
CEN	Operative temperature Cº		Acceptance*		
A	21-26**	21-23	90%		
B	20-27**	20-24	80%		
C	19-27,5**	19-25	65%		

** Rating by indoor climate surveys.*
*** Average outdoor temperature +18 Cº. (Swedish mid summer conditions).*

The perception of a surface temperature is dependent on the 'contact coefficient', which is a function of the specific heat, density and thermal conductivity of a material. Fanger (1973) has established comfort ranges and pain limits for different flooring materials for a person with bare feet. See Table 4.3.

Table 4.3 Comfort and pain ranges with bare feet for different flooring materials.

Flooring material	Comfort range °C	Pain limits °C
Steel	29-32	14/45
Concrete	27-34	4/54
Linoleum	24-35	-12/67
Oak wood	22-35	-20/74
Pine wood	17-39	-53/84
Cork	5-42	-140/150

Diagram 4.1 displays the impact of temperature on people at work according to Wyon (1986) The diagram indicates that there is a range of approximately 5°C, within which 80% of the population is satisfied, which is the highest average satisfaction obtained in this study. Exceeding this 5°C-range the satisfaction drastically drops. The position of the range is dependent on the type of activity and clothing. For example: By physical activity with winter clothing the satisfaction range is between 17 and 22°C, while sitting with summer clothing, the range of satisfaction is from 21 to 26°C. At a workplace the economic and also accident related consequences of indoor temperature can thus be quantified.

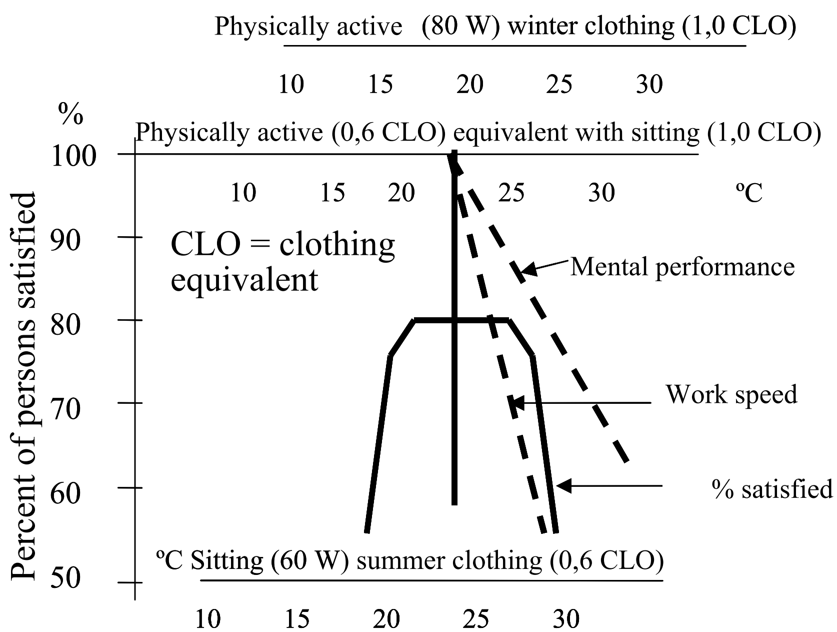


Diagram 4.1 Human performance, satisfaction and risk for accidents in work environment related to temperature, level of activity and clothing. After Wyon (1986).

Basically, prediction of thermal comfort in buildings and estimations of the required heating, and cooling effects, deal with the same physical parameters as the energy balance calculations described in Section 4.6. Principally the same calculation tools can therefore be applied. In practice, however, thermal comfort is calculated for one or a number of rooms during peak load conditions, which are the hottest and coldest days during a representative year, for the particular geographical location. Energy balance calculations used to design thermal insulation, on the other hand, respond to the integrated heating requirement for a whole year. In practice also different specialists, in the design process, deal with these two aspects. The structural designer and architect design the insulation of the climate shell, while the heating and ventilation expert deal with thermal comfort.

Traditionally, Swedish residential buildings have only been subject to a rudimentary analysis with regard to thermal comfort. Normally this has been adequate since:

- Swedish buildings have a relatively high standard of thermal insulation, which secures comfortable temperatures during the winter.
- The temperate Swedish summer climate in combination with the traditional building design with heavy structures and moderate window areas satisfies the summer case in multi-dwelling buildings.

Trends towards larger windows and lightweight building techniques results in a less robust indoor climate. Therefore careful design is needed, to avoid excessive indoor temperatures, without compromising the energy performance of the building. Increasing requirements on energy efficiency, cf. Section 4.6, furthermore emphasise the need for holistic indoor climate design. Collaboration between architect, structural designer and HVAC specialists is needed, from early phases in the project. The example with solar gains that should be maximized during the heating season and avoided during summer, illustrates this.

4.3.3 Indoor climate quality aspects – indoor air pollutants

4.3.3.1 Emissions from building materials

Building components, surface materials and furnishings to various degrees emit species to the indoor air. These may originate from solvents, preservatives, other additives or the material in itself. It is regarded necessary to restrict these ‘self-emissions’ from new materials (Corner and Norrby, 2004). The emission may increase due to reactions that are started by faulty handling of materials during production or from unsuitable combinations of materials. Moisture is often involved in these cases. Certain emissions from materials, may also react with air pollution from the building ambient, forming compounds that are much more irritant and harmful than the material emission itself. (Wolkoff et al, 1997). For example, NO_x or ozone, occurring in city air, may oxidize terpenes from building materials, resulting in free radicals and finally formaldehyde.

There are reliable methods to measure concentrations, expressed in $\mu g/m^3$, of particles of specific sizes and species in the air, as well as emission rates from materials, expressed in $\mu g/m^2h$. The health effect of specific species on humans is, however, not fully established. There are recommendations in building regulations and guidelines regarding, for instance, the maximum contents of ‘TVOC’, Total Volatile Organic Compounds. However, it is acknowledged that this is only an indicator of the amplitude of emissions and that it says little about the health effects, of the particular species in question. Criteria for maximum concentration of specific species and for particles can be found in for example FISIAQ (1995) and Sundell et al (1997).

In Finland a system for classification of materials with regard to self-emissions is applied (RTS, 2004). Classes M1 and M2 define threshold values of TVOC, formaldehyde, ammonia, carcinogenic compounds and odors, at an age of the building of four weeks. Class M3 refers to materials that do not qualify for either M1 or M2. Such M3-materials are restricted to a maximum of 20% of the surfaces, or a total of 1 m^2, of a room.

CEN (2004) has established the following criteria for a 'low polluting building material'. Other materials are defined as 'non-low polluting materials'. CEN states: *The building is low polluting if the majority of the materials are low polluting. Low polluting materials are traditional materials, such as stone and glass, which are known to be safe with respect to emissions, and materials, which fulfill the following requirements:*

1. *The emission of total volatile organic compounds (TVOC) is below 0,2 mg/m^2,hour.*
2. *The emission of formaldehyde is below 0,05 mg/m^2,hour.*
3. *The emission of ammonia is below 0,03 mg/m^2,hour.*
4. *The emission of carcinogenic compounds (IARC) is below 0,005 mg/m^2,h.*
5. *The material is not odorous (dissatisfaction with the odour is below 15%).*

4.3.3.2 Emissions from occupancy

One person generates approximately 20 l CO_2 per hour at low physical activity (CIB, 2003). CO_2 is by typical concentrations in residential buildings not related to any health aspects in itself, but indicates if the ventilation is sufficient in relation to the number of people in a room. Furthermore odour from cooking and CO from tobacco smoke, is also generated from occupancy.

4.3.3.3 Moisture

The indoor air humidity affects our perception of indoor comfort and it affects 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. The humidity will reach a balanced level a certain time after construction, depending on indoor moisture sources, temperature and ventilation. There is also a seasonal variation in air humidity, linked to the outdoor climate conditions.

Variations in humidity are to a certain extent balanced by the hygroscopic activity of building materials. Materials also have different durability with regard to moisture exposure. Typically, the durability is reduced when moisture content is increased in a material.

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.

In Diagram 4.2, an optimal or safe zone for relative humidity has been proposed.

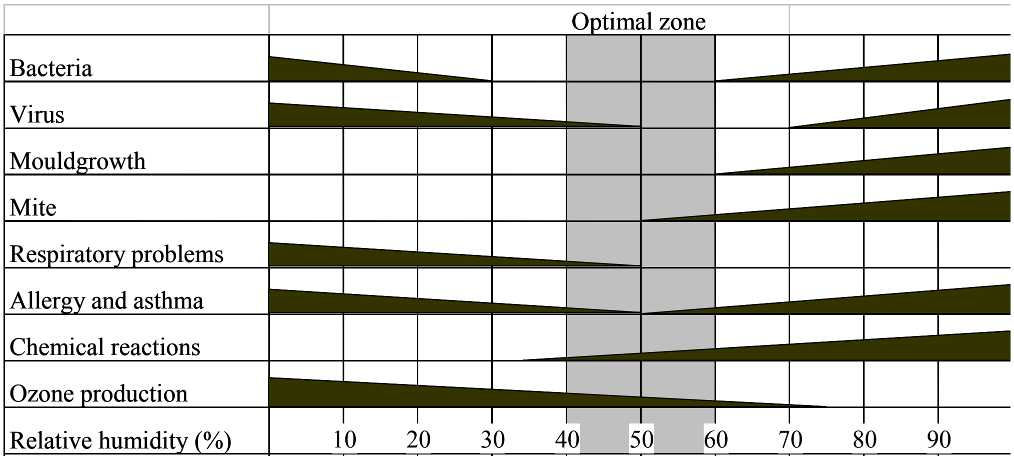


Diagram 4.2 Optimal indoor relative humidity according to Hjertén et al (1996). Increased height on triangles => increased risk.

One person at rest generates about 50 g of water vapour per hour. The additional water generated by activities in a dwelling building such as washing and cooking is well known. For example for a flat occupied by two persons the typical moisture generation is 8 kg per day according to CEN (2004).

A technical solution or system can be more or less robust with regard to moisture. Methods to deal with this are outlined in Section 4.8.

4.3.4 Quality indicators of indoor air

The concentration of different species and particles, as well as the air humidity, in the indoor air, and their connection with sources, is relatively well known as presented above. The sources are:

- Biological, such as human exhalations, mite and mould.
- Outside air pollution.
- Emissions from materials.
- Occupants activities such as cooking, washing or smoking

The indoor air quality is controlled by exchange of air with the building ambient. The air exchange consists of an intended part – ventilation, and an unintended part - air leakage. For new Swedish multi-family dwelling buildings the dominating principles for ventilation are either mechanical exhaust ventilation, or supply and exhaust ventilation, whereby, fans control both the intake and the exhaust air. Cf. review in Annex 4.A.2.

In the building regulations there are general minimum requirements on air exchange rates for buildings, with additional requirements for certain rooms such as bathrooms and kitchens. For residential buildings 0,5 air-changes/hour, corresponding to 15 l/s and person, is an often-used minimum limit in standards and building regulations (Boverket, 1998). CEN (2004) envisages how to estimate the required air exchange with regard to the pollution from both occupants and materials, taking into consideration if the material is 'low polluting' or 'non-low polluting' as defined in Section 4.3.3.1. This separation between sources is needed if the ventilation rates should be operated with variable airflow to save energy. For residential buildings CEN (2004) also defines three general classes with regard to indoor air quality, with A: 0,7, B: 0,6 and C: 0,5 air-changes per hour, cf. the temperature classification in Table 4.2.

Air tightness between different flats and through the climate shell is important for a number of reasons. The shielding function with regard to air, fire, noise and odours is directly dependent on air tightness. Air velocity is a parameter with regard to the perceived temperature, as described in section 4.3.2. Draught thus increases the required air temperature needed to acquire thermal comfort.

4.3.5 Assessment of indoor air quality in residential buildings

The quality of indoor climate can be assessed quantitatively by physical measurements, and qualitatively by tenant questionnaires on the perceived indoor climate. A pallet of verification methods for indoor climate is thus available. Aspects that are assessed qualitatively are often expressed in terms such as 'PPD-index', Predicted Percentage of Dissatisfied, defined in ISO 7730, *Moderate thermal environments – determination of PMV and PPD indices and specification of the conditions for thermal comfort*, compare example on acoustics in Diagram 4.3. With the 'PMV-index', Predicted Mean Vote, people grade thermal comfort on a 7-step scale from –3, very cold, over 0, neutral to +3, very hot.

The air quality in Swedish residential buildings is normally assessed indirectly, by checking the flow in the ventilation valves. A more precise method is to measure the CO_2 concentration. In guidelines, limits for CO_2 concentrations between 700 and 1500 ppm can be found (CIB, 2003, FISIAQ 1995, Sundell et al 1997). CEN (2004) defines 3 classes: A: 350, B: 500 and C: 800 ppm higher than the outdoor CO_2 concentrations. The air exchange to maintain a steady state CO_2 concentration can thus be calculated for any specific case. The following example refers to CEN class B: For three persons occupying a 100 m^2 flat with an air volume of 250 m^3, the required air exchange is thus 0,39 air changes per hour, to maintain a steady state CO_2 concentration. The assumptions where an outdoor air CO_2 concentration of 380 ppm and the exhalation of CO_2 20 l per hour and person according to CIB (2003). This can be compared with the requirement of 0,5 air changes per hour in the Swedish building regulations (Boverket, 1998).

4.3.6 Concrete and indoor climate

Concrete is an inorganic material with capability to buffer heat and moisture. It can thus contribute to a healthy and comfortable indoor climate. With concrete structures in façades and roofs, functioning as vapour barrier and structural material, the risk for condensation of moisture and related problems are negligible. Touching a concrete surface with a naked hand or foot, gives a relatively cool sensation because of the high contact coefficient, c.f. Table 4.3.

Several investigations regarding primary emissions from concrete, for instance Wengholt (1995) and Hjellström (2004) confirm that there are only small, and probably negligible, self-emissions from the material, 2-4 weeks after casting. This is the case also for concrete with relatively high doses of chemical admixtures or mineral additions, which may be utilized at the production of cement and concrete. Comparing the reported results with the CEN classification, cf. Section 4.3.3.1, concrete with a large margin qualifies as a 'low-polluting material'. Concrete structures are classified in the safest, M1, category according to the Finnish system for classification of self-emissions of building materials, cf. Section 4.3.3.1.

Sick building symptoms in connection with concrete structures primarily relate to secondary emissions from floors with polymer-based flooring systems. Inadequate drying of the concrete after casting, or after a water-damage, or additional moisture from the adhesive, used to fasten the carpet, may activate a process where the flooring material, or the adhesive layer under the flooring material, is decomposed by hydrolysis. Sjöberg (2001) concludes that both moisture and alkalinity are needed to trigger this reaction.

During the 1990s 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, due to the low water to cement ratio required. It has been discussed, whether the higher alkalinity of these cement rich concretes may increase the risk of emissions. Experience shows, that this potential problem is related to the additional water from the adhesive that the self-desiccating, dense, concrete is not capable of buffering. This might induce a critical combination of alkalinity and moisture. Solutions to this problem, in order to eliminate either the alkalinity or the moisture condition, are either to apply a low alkali screed on the concrete or to use an adhesive that does not add water.

Self-desiccating concrete gives an opportunity to increase thickness of concrete floors, for the purpose of, for instance, enhanced load carrying capacity and sound insulation, without prolonging production time due to drying of concrete. Also compare Section 4.8.4.

An adequate computer tool for the moisture design of concrete structures including material data, TorkaS 2.0 (2002), is available, as well as reliable methods to measure the moisture content in a floor, before the application of adhesives and flooring materials (SBF 1997).

Integrated life cycle design and indoor environment:
In order to systemise the criteria a distinction is introduced between:
- Health related aspects, whereby requirements, typically stated in norms, are screening criteria that cannot be subject to any ILCD optimisation.
- Comfort requirements where a specific quality level can be selected.

A system for classification and verification of comfort requirements, after Carlsson et al (2004) and CEN (2004), is applied in this work. It contains three indoor climate classes: ICC A, ICC B and ICC C, in principle referring to best available, good and 'according to norm'. The method covers: Thermal comfort, air quality and acoustics (Acoustics cf. Section 4.5). It comprises quantitative criteria as well as a qualitative assessment model based on indoor climate surveys.

Table 4.4 Criteria for thermal comfort after Carlsson et al (2004) and CEN (2004)

Aspect	**I**ndoor **C**limate **C**lass	**Unit**	**ICC A**	**ICC B**	**ICC C**
Operative temperature	Winter Summer	°C	20-27 19-27		> 18 > 18
Floor temperature	Minimum Maximum	°C	19 27		16 27
Air velocity, maximum		m/s	0,15		

Table 4.5 Criteria for indoor air quality after Carlsson et al (2004)

Aspect	**Unit**	**ICC A**	**ICC B**	**ICC C**
Fresh air flow	L/s per m^2 floor area*	0,49	0,42	0,35
Relative humidity	RH, %, winter	40-60	30-60	30-70
CO_2	ppm, Room air Intake air	800 600	800	1000

** Equivalent to 0,7; 0,6; 0,5 air changes/hour by 2,5 m floor height*

4.4 Safety in use. Essential Requirement no 4

Safety in use according to the Construction Product Directive deals with user risks such as slipping, falling, drowning, electrical accidents. These aspects are usually covered by unconditional, detailed and prescriptive requirements in the building regulations. They have therefore relatively little relevance for integrated life cycle design of a building, and will thus not be expanded on in this study. In an overview of functional design criteria by Lagerqvist and Johansson (2004), the aspect of mechanical protection against housebreaking is addressed, in this context. Three protection classes, related to a risk classification used by insurance companies, are defined in SSFN, (1994), For a residential building, in a normal ambient environment, the lowest protection class, 'Sk1', is deemed sufficient.

Concrete and safety in use

Concrete structures are well suited to fulfill the safety in use requirements. A partitioning wall or floor of concrete of normal thickness for residential buildings, that is at least 160 mm, exceeds the requirement highest protection class (100 mm), Sk3 for housebreaking, mentioned above (SSFN, 1994). A composite exterior wall requires two leaves of concrete 40mm + 60 mm for Sk1 and 60 mm + 60 mm for Sk2 and Sk3. Exterior walls with inner leave of concrete and outer layers of other materials, such as rendering on thermal insulation are not defined.

***Integrated life cycle design with regard to safety in use*:**
For dwelling buildings safety in use is covered by prescriptive unconditional building regulations and cannot be subject to any ILCD optimisation. Housebreaking is addressed with the system of protection classes according to SSFN, (1994)

4.5 Acoustics. Essential Requirement no 5

4.5.1 Noise in multi-dwelling buildings

SOU (1993) states that good sound insulation ranks among the most vital quality factors for residential buildings. In the study the satisfaction with sound insulation and the willingness to pay for improved quality was examined. Five existing Swedish residential areas were surveyed, all of which, according to measurements, fulfilled the acoustic norm requirements for new buildings. 30% of the respondents answered that they were disturbed by internal noise in the building. To gain a full satisfaction, in this regard, the households were willing to pay 2,3-3,3% higher rents.

The important sources for noise disturbances in residential buildings are:

- Noise caused by human activity in neighbouring flats or common areas inside the building, such as staircases and elevators.
- Noise from technical systems inside the building.
- Noise from outside the building.
- Noise from inside the apartment.

Diagram 4.3, shows the average complaint distribution regarding noise in Swedish residential buildings built from 1985 to 1990 (Engvall and Norrby, 1992).

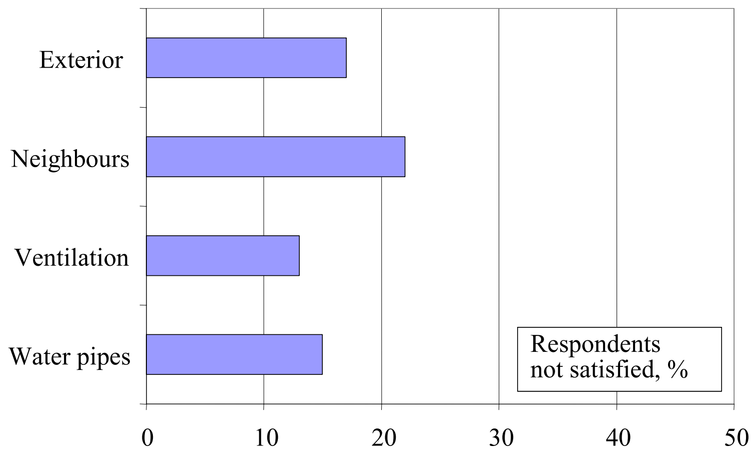


Diagram 4.3 Noise complaint distributions according to source in modern Swedish multi-dwelling buildings according to Engvall and Norrby (1992).

The transport of sound inside a building depends on both the direct airborne sound through the partitioning structures, the impact sound insulation and the flanking transmission. Flanking implies indirect transmission through the surrounding structures. Small deficiencies, such as cracks or holes in structures, may ruin the sound insulation.

4.5.2 Acoustic regulations and design tools

The Swedish building regulations, BBR 99 (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 BBR 99, the next lowest sound level class, C, is the minimum quality level for new residential buildings. Sound class B is regarded as a minimum standard for good quality dwelling buildings according to Åkerlöf (2001). Table 4.6 presents requirements on sound insulation and examples. Hammer and Nilsson (1999) discusses the Swedish classification and points out that it may not be appropriate to use the same ranges and number of classes for airborne and impact sound classification.

Table 4.6 Sound insulation classification according to Swedish building code and examples of perceived noise from neighbours (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	May be heard	54	May be heard
C	52	May be heard	58	May be heard
D	48	Heard	62	May 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 data for single components. Additional layers, connections, the building layout and also the relation with regard to density and stiffness between adjoining structures have to be considered.

The acoustic performance of a specific design can be predicted by calculation, and the achieved performance can be measured. The results referred to in Section 4.5.1, however, indicate that current classification does not fully comply with the tenant judgements.

Bodlund (1985) investigated the shortcomings of standard evaluation procedure, EN ISO 717/2, with regard to the perceived impact sound insulation, which appears to be the most critical part in sound classification. Bodlund examined a large number of multi-dwelling buildings with different partitioning floor materials. The tenants were exposed to standard impact sound tests and their judgements recorded by a seven-grade scale. An alternative reference curve with a 'Bodlund index', L_B, could thus be established.

Nilsson and Hammer (1999) studied the subjective evaluation of impact sound insulation, for eight different floor types ranging from lightweight to concrete, and confirm that the Bodlund index is significantly more representative than the current standard. Nilsson and Hammer furthermore show that by application of a 'Loudness' criterion described in ISO 532, even better correlation between measured and perceived impact sound insulation can be obtained. While the accuracy when using the standard method appear to vary with the type of structure that is assessed, the Loudness criterion gives more reliable results both for heavy and lightweight structures. Nilsson and Hammer (1999) present a set of six scales to rate the perceived impact sound by expressing the position between 0 and 10 for opposites such as not sharp – very sharp, not annoying – very annoying, not thumping – very thumping. Laboratory studies showed that the type of flooring material greatly affects human perception in this regard.

Persons involved in the application examples presented in Chapter 7, confirm a possible weakness of the current acoustic classification. It was for instance stated that the design target is sound class B, while only class C performance can be guaranteed to the client.

Acoustic design may be based on a set of international standards. These standards, EN ISO 140 and EN 12354, have been developed from theoretical models as well as practical experience. A computer programme based on these standards, BASTIAN® (1996), can be used in early design stages for a preliminary acoustical evaluation of alternative structural solutions. The programme is furnished with a database comprising acoustic input data for normal cast in place 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.

Data on acoustic performance of the individual structural element can be obtained from handbooks, such as Åkerlöf (2001) or Wikells (2000). As mentioned above, it it is not possible to determine the resulting total acoustic quality of a building with data for individual components. 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.

4.5.3 Concrete and acoustics

The advantages of concrete with regard to acoustics are related to the high density, tightness 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 from modern audio equipment. The step from sound class C to B is comparably easy to obtain for traditional concrete residential buildings. The step from class B to class A 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 deficient design of connections, leading to flanking transmission and to floor designs that do not subdue impact sound.

In a concrete exterior wall it is normally windows and ventilation openings that are critical for the direct sound reduction. The flanking transmission must also be considered, and is taken care of by a proper detailing of the connections between the façade, interior walls and floors.

Integrated life cycle design and acoustics:
For traditional concrete buildings, acoustic performance classes according to the Swedish Building Regulations, (Boverket, 1998), can be used. However, there are shortcomings with regard to this classification, particularly with regard to impact sound insulation.
The actual performance with regard to these classes can be verified quantitatively by measurements or qualitatively by questionnaires. Reliable subjective evaluation models have been outlined in recent research.

4.6 Energy economy and heat retention. Essential Requirement no 6

Energy is used through all life cycle phases of buildings, from the extraction of raw materials to demolition and recycling. The use of energy has both great environmental and economical implications. The scope of the Construction Product Directive and also the more recent EU Directive on Energy Performance of Buildings, (EU, 2002), are restricted to energy consumption during the usage phase, which is dealt with in this section. From a general environmental perspective the energy used by production and recycling must also be considered. This is discussed in Section 4.12.

4.6.1 Mechanisms of building energy performance

The energy demand for space heating and cooling of a building, during given outdoor climatic conditions and at a specific interval of indoor temperature, depends on a number of factors, which are illustrated by the energy balance presented in Diagram 4.4. The case refers to the annual energy use per m^2, for a modern Swedish multi-dwelling building, in Stockholm, with supply and exhaust ventilation and heat recovery from exhaust air.

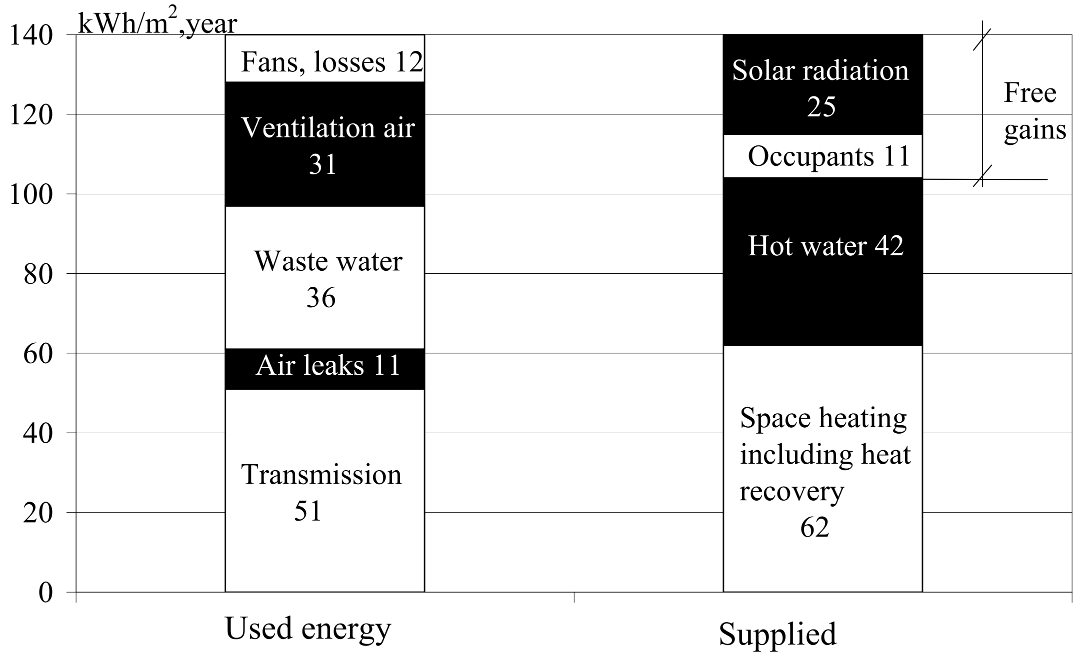


Diagram 4.4 Energy balance of a concrete multi-dwelling building with supply and exhaust ventilation built in Stockholm 1985 (BFR, 1986).

Transmission is dependent on the thermal insulation of the building, which is expressed by U-values for the different parts of the climate shell.

Ventilation losses refer to the used warm air that needs to be removed, to secure good indoor climate, cf. Sections 4.3.3 and 4.3.5.

Air leakage is convection of air driven by differences in air pressure over the climate shell, caused by wind or temperature differences within the building ('stack effect'). It is governed by the air tightness of the structures.

On the energy supply side there is a certain amount of energy that can be gained from sources other than the heating system, such as, solar radiation and energy from people and their activities. These are defined as 'free gains' in Diagram 4.4. The amount of free gains that can be utilised is governed by the active heat capacity. This refers to the capability of the building interact thermally with the indoor air and absorb, store and release heat, and thus to even out air temperature fluctuations. The main thermal fluctuation cycle in a building is the twenty-four hour period.

The required heating or cooling effect, for a specific outdoor temperature, depends on the relationship between heat capacity and energy losses or gains. This is expressed by the 'time constant', which is defined as:

$$\text{Time constant} = \frac{\text{Heat capacity}}{\text{Heat losses by transmission, air-leaks and ventilation}}$$

The time constant indicates how fast a building cools down if the heating is turned of, or by a rapid change in outdoor temperature. The heating effect determines the size and thus cost of heating and cooling systems. Further to these project costs, the maximum required effect is relevant with regard to the strain on the power nets, at peak loads. With a high time constant the possibility of use of a low exergy strategy is facilitated, cf. Section 4.12.2. An example of the calculation of time constant is given in Annex 7.C, Table 7.C.4.

According to SS (1991), the design temperature for heating is selected so that the indoor temperature does not fall below the minimum norm temperature by more than 3ºC, for the case with the recent 20-year period's lowest temperature.

Electricity used in dwelling buildings refers to:

- 'Domestic', which is used by in the flats by the tenants for lighting and different appliances.
- 'Common', referring to general use in the building for lighting in stairways, operation of elevators, fans and pumps.

In design guidelines and statistics often only the common electricity is accounted for, as a designer or owner of a multi-dwelling building has limited influence on the domestic electricity use.

4.6.2 Regulations and calculation methods for energy performance

Traditionally the energy performance of the climate shell of a building has been assessed by an elemental U-value (thermal transmission) approach, were maximum U-values for the different elements of the building have been stated in the national regulations. Some countries also have requirements with regard to air leaks. Specific requirements on ventilation, boilers and ducts are often stipulated, however, without any correlation to the properties of the building structure. The effect of thermal storage can only be indirectly taken into account with the elemental approach. This was done in the Swedish building regulations prior to 1972 (BABS, 67). Then an exterior wall with a self-weight of more than 100 kg/m^3, for instance a concrete wall, required an U-value ≤ 0,93 W/m^2°C while a lighter wall required the U-value ≤ 0,58 W/m^2°C. This implies that heavy buildings require less heating energy than light buildings, with equal thermal insulation. This correction was removed in later norms.

The EU Directive on Energy Performance of Buildings, (EU, 2002), establishes a new common European framework for energy requirements, in terms of calculation and verification methods, classification and certification of buildings.

The Directive states that calculation of the energy performance of buildings shall include at least the following aspects:

(a) thermal characteristics of the building (shell and internal partitions, etc.). These characteristics may also include air-tightness;
(b) heating installation and hot water supply, including their insulation characteristics;
(c) air-conditioning installation;
(d) ventilation;
(e) built-in lighting installation (mainly the non-residential sector);
(f) position and orientation of buildings, including outdoor climate;
(g) passive solar systems and solar protection;
(h) natural ventilation;
(i) indoor climatic conditions.

This integrated approach – a so called Energy Performance regulation including all aspects listed above, can be defined by a formula such as:

$EP \leq EP_{max}$

Where EP represents the calculated energy consumption of the building, usually expressed in kWh/m^2. EP may include a CO_2 indicator according to the Directive. EP_{max} is the national regulated limit, which may be determined in different ways. This limit is typically based on the national targets with regard to reduction of emissions leading to global warming.

Guidelines on energy balance calculations, including energy gains and thermal storage, are given in the European Thermal performance standard for buildings, prEN ISO 13790 (CEN, 2003) 'Thermal performance of buildings – Calculation of energy use for heating'. This standard presents the energy balance of a building schematically, according to Figure 4.3. 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.

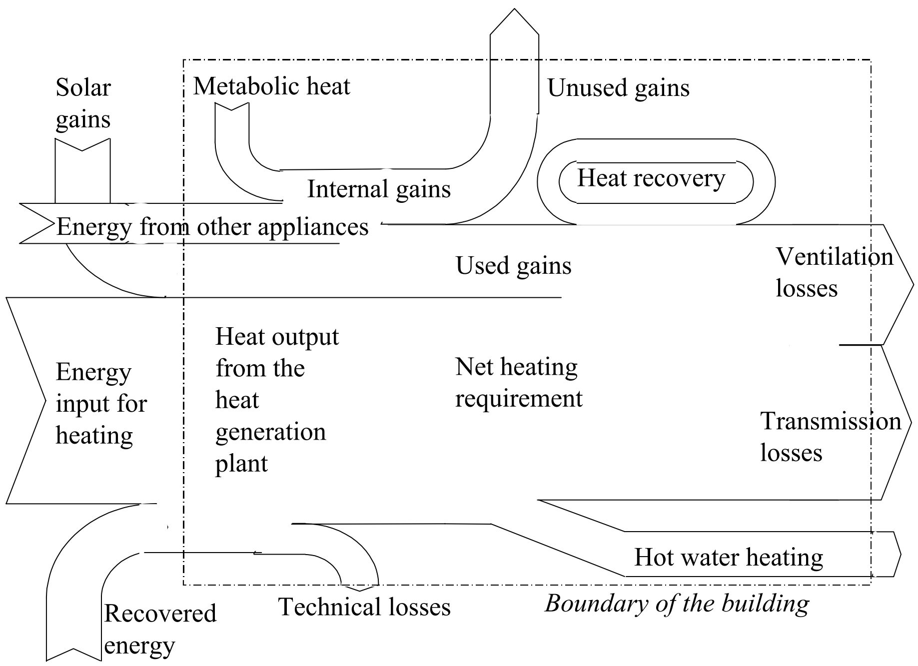


Figure 4.3 Energy flows for calculation of energy balance for a building according to prEN ISO 13790. Metabolic heat is heat buffered the structure.

The EP approach is already operative in many European countries, for instance in Sweden, typically as an alternative to the elemental U-value approach. The EP of a building can be assessed in different ways, from simple 'hand book' methods, over semi empirical computer models, to detailed dynamic computing models. The EP includes at least transmission, ventilation and internal and solar gains. The trend is to introduce more energy flows such as hot water and lighting in the EP calculation.

With the EP approach the issue of indoor climate can be integrated in a logical way. Air quality (ventilation rate) and thermal comfort during summer, and the energy consequences of cooling can be included. The Energy Directive specifically points out that:

- Measures to improve energy efficiency must take other building requirements and in particular indoor climate into account.
- Energy use for cooling of buildings is also restricted.
- Buildings should be developed so that the top effect, required by peak loads, which increases electricity costs and disrupts the energy balance, in many European countries, should be lowered.

4.6.3 Current energy use and future goals for Nordic residential buildings

According to 'Miljövårdsberedningen' (2000), the average annual energy needed, in a recently built multi-family residential building, for space heating and hot tap-water is 140 kWh/m² and the use of electricity is 35 kWh/m². Normally 1/3 of the electricity is common and the rest domestic. These figures conform to Erlandsson (2004), who states 144 kWh/m² for space heating and hot tap-water, and 46 kWh/m² for electricity, of which 16 is the common part. A share of the electricity generates heat that reduces the heating requirements, which is taken into account by energy balance calculations.

National Swedish goals 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).

In Finland the more progressive energy performance criteria according to Table 4.7, have been issued (RIL, 2001). Several houses have been built in Finland conforming to the class 'Minimum' requirements. In a demonstration project it was shown that the 'Minimum' level was optimal from a life cycle cost perspective compared to 'Standard' and 'Low', showing that investments in enhanced energy performance are profitable.

Table 4.7 Energy performance classification according to Finish guidelines.

Class	Comment	Heating + cooling	Total*
		kWh/m²,year	kWh/m²,year
Standard	Current standard	120-180	150-200
Reduced		60-80	100
Low		30-40	60
Minimum		15-20	40
Zero	Active energy gain required (e.g. solar)	0	20
Plus			

** Including lighting and other use for building services*

From the environmental perspective, the impact of particular energy sources varies. To estimate the actual environmental burden of the energy consumed by a building, the types of energy sources should therefore be separated, and if possible the primary energy consumption quantified. The CO_2 indicator in the Energy Performance of Buildings Directive mentioned above serves this purpose. This can, for instance, resolve the question of how much district heating must be saved by a heat pump that operates on electricity in order to be environmentally viable. There are however, some technical and principal difficulties involved in these considerations, which are further discussed in Section 4.12.2.

4.6.4 Concrete and energy use in buildings

The energy saving potential of concrete buildings are related to thermal storage, and when concrete has the function of a vapour barrier in the climate shell, also to air tightness (Elmroth, 1996). Besides limiting the overall energy requirement for heating, these properties, and in particular thermal storage, also decrease the top effect required for the heating and cooling system, cf. Time-constant in Section 4.6.1.

The thermal storage depends on the effective heat capacity, i.e. the share of the total heat capacity that contributes to the heat exchange, between the structure and the indoor air, during temperature fluctuation cycles. Furthermore, to utilize thermal storage, the indoor temperature must be allowed to vary 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 $W/m^2K°$. 180 mm of a concrete interior wall or slab is thus accessible for thermal storage. 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. In Annex 5.F comparative calculations on energy use in buildings with different heat capacity are presented.

If an intermittent heating regime is used, high thermal capacity will, on the contrary, increase the energy consumption (Markus and Morris, 1980). For a permanent residential building the intermittent mode of operation is, however, seldom used. The relatively small energy gains that are obtained are not motivated in relation to the much higher effect requirement and the decreased thermal comfort by intermittent heating. Energy balance programmes can model the consequences of different operating modes with regard to top effects and energy use.

Akander (2000) calculated the difference with regard to potential energy requirements in Swedish multi-family dwelling buildings with different thermal inertia. A dynamic energy balance calculation programme and also the above-mentioned European standard were applied. The conclusion was that the energy required for heating the heavy building was 86-94% of the light building, depending on the specific conditions.

Concrete, however, has high thermal conductivity. Hence a careful design to avoid heat bridges is essential, as these may contribute to a substantial part of the energy losses, if improperly designed.

Integrated life cycle design and energy performance:

Energy performance is a main contributor to the life cycle environmental burden, as well as life cycle cost, of a dwelling. Furthermore it is, highly dependent on the design of the building. Accordingly energy performance requires close attention by ILCD.

Target values for energy use can be defined and estimations can be made with adequate energy balance prediction tools. A set of classes of energy performance simplifies the specification. After a model presented by Erlandsson (2004) and the Finish model presented in Table 4.7, four classes for energy performance of new buildings are proposed.

Class	Total bought energy for space heating, hot water and common electricity** (kWh/m^2)	Of which maximum electricity (kWh/m^2)*
0. Best available	50	15
A. Best practise	70	15
B. Good	90	20
C. Norm	120	25

** Higher electricity share allowed if total energy is reduced by n x exceeding electricity use. Where n compensates for the environmental impact of electricity in relation to other energy carriers, such as district heating.*

*** Domestic electricity excluded as a designer or owner of a multi-dwelling building have limited possibility to influence this.*

4.7 Durability

All materials, systems and components are subject to degradation processes depending on the specific ambient and load conditions. By the composition of the material or product, protective measures and maintenance actions the service life can be controlled. If design lives for the elements of the building are defined, the design for durability is an optimisation problem. To support life cycle design, data on service life and maintenance requirements for strategic materials, components and systems are needed. This information can be organised in a maintenance plan for each design alternative. Compare example in Section 7.8. The maintenance plan is a basis for life cycle appraisal of costs and environmental impacts, which can aid choices between materials and components. The maintenance plan for the selected alternative can later be utilised by facility management.

As mentioned in the introduction of this chapter, the scope of durability requirements in building regulations is limited to the essential requirements. The CPD (1988) states that *the essential requirements should subject to normal maintenance, be satisfied for an economically reasonable working life*. From the client's point of view, with regard to maintenance costs and environmental efficiency, all components of the building and all their intended functional properties are relevant for durability considerations.

For planning and design purposes, classification of service lives of materials and structures is practical. Caluwaerts et al (1996) presents a sequence of 10 years, 30 years and >50 years. This, in principle, agrees with the modular design approach in Section 3.3.6, and the Open Building concept discussed in Chapter 9.2.3. Similar figures have been published by the EU (2004), which has defined a classification to help clients to avoid unfair competition between construction products. The scheme relates to the exchangeability of components. The 10 year interval is proposed for products which can be 'repaired or easily replaced', the 30 year interval when replacement 'requires some effort' and >50 years shall correspond to the life span of the entire construction.

The European structural design standard prEN 1990, CEN (2001) gives examples of four service life classes: 1-5 years for temporary structures, 25 years for replaceable structures, 50 years for building structures and finally 100 years for monumental building structures and bridges. This type of definition is common in other building regulations. The Swedish concrete construction guidelines recommends 50 years for parts that are accessible for inspection and repair, and 100 years for structures that are not.

From the client point of view the 'exchangeability' aspect is valid for service life design. However, only as one of the factors in the overall consideration, which also involves functionality, life cycle cost and environmental efficiency.

There are different approaches to durability design, such as:

- Quantitative deterministic analysis of the time dependent process of degradation of the material or structure. The analysis has to be based on quantitative information of all relevant environmental exposure factors and material parameters involved in deterioration, and also on a profound understanding of the destruction process, cf. concrete and durability below.
- Quantitative probabilistic analysis. Here the quantitative deterministic analysis is supplemented by a probabilistic, reliability theory. The degradation phenomena are described with known or assumed standard deviations, with relevant distribution functions. The probabilistic approach enables quantification, for instance with regard to economy, of different risk levels, related to the alternative designs available.
- The safety factor concept, which is analogous to the structural design principles. Based on the methods mentioned above, it uses partial safety coefficients to deal with the exposure as 'load' and material durability as 'resistance', Sarja (2003).
- Experience based method were reference data on length of life of a material or component, subject to specific exposure conditions and maintenance, is used. This method is not safe for new materials, new construction concepts or new exposure conditions.
- The factor method is a qualitative concept, where the service life is estimated by multiplying non-dimensional numerical values, representing a set of durability factors. This method is presented in the ISO 15686 series of standards (ISO, 2000), which are reviewed by Sjöström and Lair (2003). According to the standard the factors are: Quality of component, design level, work execution level, indoor environment, outdoor environment, in-use conditions and maintenance level. The method postulates that the service life can be modelled by linear multiplication of the all the different factors involved. The justification of this postulate is not clarified in the ISO standard.

In building regulations, durability requirements are often defined in descriptive terms, that is, a specific material quality is given for a particular exposure situation. However, criteria can also be performance based, for example, as the freeze-thaw test applicable for concrete.

Concrete and durability

Concrete structures can be designed and optimised for durability and long service life, without any need for surface protection or maintenance. Quantitative – probabilistic methods, as referred to above, are available. An example is the European Union Brite EuRam III project *DuraCrete,* on service life design of concrete. In DuraCrete (1999a) a summary report of this project is given, showing the principles of probabilistic service life. The required information on the interaction between environment and material - the destruction mechanisms - is furnished in DuraCrete (1999b).

Sarja and Vesikari (1996) discuss probabilistic service life of concrete. Practical methods for probabilistic service life design are described by Vrouwenvelder et al (1998).

The primary degradation factors for reinforced concrete in Swedish multi-dwelling buildings are:

- Corrosion of steel reinforcement, which is governed by the time dependent depassivation of steel by carbonation of the concrete. The corrosion attack is intensified by the presence of chlorides such as may occur in case of use of de-icing agents. The design parameter for corrosion is protection of the steel, which is determined by the quality and thickness of the concrete cover of the reinforcement. The water to cement ratio is, for this case, the most decisive concrete quality factor.
- Frost damages of concrete can occur by repeated freezing and thawing in presence of moisture. Also this attack is intensified in the presence of chlorides. Frost resistance is controlled by the concrete composition of which the water to cement ratio, and particularly the presence of an entrained air pore-system that permits expansion of freezing water, are fundamental parameters.

The well-established relationship between design parameters and degradation mechanisms of concrete allows a rather precise determination of service life of concrete structures. Guidelines and regulations on durability design of concrete in relation to a wide range of different exposure categories are found in the European material standard for concrete, EN 206-1 (CEN, 2000), and associated national application documents. Both descriptive and performance based design models are available and outlined. For interpretation of the exposure classification for Swedish applications, guidelines are given in SBF (2002).

The most aggressive environment related to residential buildings are exterior surfaces exposed to de-icing salts such as stairs or balcony access 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 regarding concrete composition or reinforcement cover. Other, more moderately, aggressive conditions are wet indoor climate, such as bathrooms or surfaces exposed to freezing and saturation from fresh water, such as façades.

Most concrete in residential buildings is used inside the climate shell. Here the carbonation rate is high but as the environment is dry, as well as warm, there is no degradation of the structures.

In the desk top study presented in Chapter 6 an example of deterministic durability design of concrete is given.

***Integrated life cycle design and durability*:**
Adequate durability, and furthermore the possibility to predict the durability, of components and materials is a key to lifetime optimisation of buildings. The predictions can be based on economical and environmental analyses of a maintenance plan. This plan should cover the strategic technical systems, components and materials for the design alternatives that are examined.
The data needed to compare different materials or components with regard to durability are from the economical point of view:

- i) design life
- ii) maintenance interval
- iii) cost of maintenance activity including residual value or disposal costs of components taken out of the building

and from the environmental point of view additionally:

- iv) environmental burden of maintenance activity
- v) recycling aspects

The data i-iii are available from different sources. For the Swedish residential building application this has been compiled in a data sheet within the life cycle costing module of the ILCD toolbox, cf. Section 5.2.6. The data iv, and v can presently be obtained only for some materials and components. In the Finnish LifePlan research project (Häkkinen, 2003), a system for life cycle inventory data to be supplied by a product specific database is outlined. The information includes service life, performance requirements, care-taking and maintenance.
For concrete precise quantitative predictions of service life can be done, for the specific ambient environmental exposures according to SBF (1998).

4.8 Robustness

Robustness is in this work defined as a general capability to avoid or withstand any, more or less, expected incident or condition, both with regard to construction and user phase. This is linked to mechanical characteristics and durability of individual components and materials. It is, however, also an integral design issue, that is dependent on the interaction between components, and also on the technical detailing or concept. Robustness is therefore regarded as a specific risk related attribute covering:

- Technical solutions and systems that have a high inherent safety margin. A flat roof is, for example, less robust than an inclined roof with regard to water leakage.
- Ability of materials, structures and systems to withstand unforeseen mechanical or building physical loads.
- Possibilities to repair a structure after damage.
- Residual capacity in the structure to enable changes in terms of increased loads or introducing openings in an existing structure, etc. cf. Section 4.9.
- A technical solution, or production method, that is less susceptible to conditions on site and is tolerant with regard to quality of execution.

4.8.1 Robustness by construction

Robustness by production relates either to the influence of the ambient climatic and physical conditions by storage, transport and production or to how well technical solutions are designed with consideration of 'constructability'.

The selection of materials and components must be in tune with the production methods that are available. Feed back from the site to the designers on details that are difficult to execute and verify, is also important.

4.8.2 Robustness during use of the building

Robustness of the user phase implies avoiding risks from the building physical or structural point of view. Some examples, many relating to humidity and water:

- Mechanically susceptible materials or technical detailing.
- Air-tightness relying on sensitive or not durable materials and complicated technical detailing.
- Design, materials and detailing, which are susceptible to water, (Leakage from internal or ingress from external sources), for example flat roofs.
- Technical solutions where humid indoor air meeting may meet cold surfaces and condensate, such as heat bridges or poor air tightness.
- Technical solutions that do not prevent transport of water or moisture from the ground.
- Excessive temperatures, depending on problems to maintain acceptable indoor temperatures by malfunction of heating and ventilation systems.
- Fire safety depending on complicated and non-durable technical solutions.
- Technical systems or materials that require regular maintenance and control.

In multi-dwelling blocks, mechanical damage is primarily concentrated to common and accessible areas such as stairways, basements and street level façades. Water damages has certain similarities to damages by fire, compare Section 4.3, in that the total extent of the damage depends on the ability of the structure to confine the spread of water, in parallel to fire. The severity of the damage is furthermore dependent on the specific materials susceptibility to water. Furthermore, water damages constitute a large share of the damages after fires.

Moisture is important with regard to degradation of materials and, therefore, both relevant to indoor climate and maintenance costs. Moisture behaviour of building structures is dependent both on material characteristics, design and execution.

The climate shell of the building, which is exposed to moisture or water, needs 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. A crawl space ventilated by outdoor air is a more sensitive solution, since it becomes very humid, particularly during the summer. Organic materials should therefore be avoided in the crawl space structure and the floor above it should be absolutely airtight, in case that mould growth occurs on any organic matter or if other contaminants appear inside the crawl space. Airtight ground structures furthermore decrease the risk for problems with any radon present in the ground.

Buildings need to be constantly airtight, both over the climate shell, and over time. An air tight climate shell is a prerequisite to achieve even and adequate ventilation rates in different rooms, to avoid the risks of condensation of moist indoor air in the exterior walls or roof, and finally to limit energy use for heating (Elmroth, 1996). Condensation may lead to decreased function of insulation materials, mould growth in organic materials and general degradation of structures. Above all, buildings with supply and exhaust ventilation, but also with natural ventilation, are sensitive from this point of view. The risk of interior overpressure in buildings with these ventilation concepts is higher than in the case of exhaust ventilation systems. The ceiling and its connection to the exterior walls, on the lee side of the building, are particularly sensitive with regard to this, due to the combination of wind and the stack effect, which drives indoor air upwards. By internal overpressure moist indoor air may infiltrate the climate shield, if it is not sufficiently airtight. The moist indoor air will then at some point in the structure reach the condensation temperature.

In massive structures, such as concrete outer walls, no specific measures need to be taken as regards air tightness. 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 constitute the air and vapour shield.

Special care should be taken to design and execute the connections in such cases. The plastic foil should be protected from mechanical damage and its long-term durability must be ensured.

Increased insulation in ventilated roofs may lead to low temperatures that must also be considered carefully to avoid condensation. A typical conflict between architectural design and building physical considerations is the horizontal roof, which is risky from the water tightness point of view and requires heated rainwater drainage ducts in cold climates.

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

A general review on building physical robustness of buildings, including recommendations, is presented by Hagentoft (2003).

4.8.3 Methods to ensure robustness

Theoretically the selection of more or less robust alternatives could be based on risk analysis referring to the probability of damage and the consequences of failure. The standard on Service life planning, ISO 15686-1, presents a hierarchy of consequences in eight steps ranging from 'No exceptional problem' to 'Danger of life'. This method could be used by large-scale product development, such as for type-buildings, but for the ordinary multi-dwelling project this is not a realistic method. The more direct approach of utilizing the experience of the performance of similar existing structures, systems and their interaction, is deemed to be appropriate in this context. This refers both to production and user phase robustness aspects and is discussed in Section 5.7.

The experience approach may, however, hinder technical development. Yverås (2002) has presented a method of performance indicators based on the experience of the performance of existing types of technical solutions. The concept has a multi-cause approach, also open to assess new designs. The method is based on the repeated analysis and feed back to the knowledge base, of the performance of cases under different ambient conditions. Its contribution to decision making is that complex contexts can be addressed without having solved all the mechanisms involved. The method is tested on one pilot application – crawl space foundations. The concept is, however, general and could be adopted, for example, for a limited number of strategic structures and systems.

Sandin (1998) proposes a method to address moisture safety of constructions based on a combination of a qualitative assessment, proven technical solutions and quantitative predictions of moisture transport, applying climate data for the particular location.

To provide relevant data for moisture calculations, a database with climate data for ten different locations in Sweden has been compiled. This is free to download from ‘the Moisture center’ at Lund University, and is described by Harderup and Harderup (2000).

These methods combining experience with quantitative predictions may appear cumbersome. However, for a Swedish multi-dwelling building the number of crucial components and aspects are limited. A generic list of items for qualitative-quantitative design is proposed in Section 5.8 and an example is given in the desktop example presented in Chapter 6.

From a general risk point of view the robustness of buildings in Sweden, are 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. (REPAB, 2000). For dwelling buildings the damages are dominated by water leakage and fire (Kjell, 2004). The insurance rate is a simple ILCD criterion, based on statistics of damages. The robustness can, in that case, be economically quantified by a life cycle cost calculation, which will favor the more robust design alternative.

For the assessment of different design solutions on component or system level, this criterion is rather coarse, however. On a more detailed level the aspect of robustness is difficult to express as one clear design criterion. Many of the factors that assembled constitute a robust technical solution are addressed under other attributes with regard, primarily, to building physics. A combined qualitative and quantitative valuation, as mentioned above, is envisaged as a practical method to this end.

4.8.4 Concrete and robustness

Robustness is, in a broad sense, a typical feature for concrete in the finished building, due to its strength, stiffness, density and inorganic composition. The capacity to buffer heat stabilizes the indoor climate, which also provides a sort of robustness.

By production of concrete floors the moisture conditions must be considered when attaching bonded organic flooring systems. There are both design and control tools available for this, cf. Section 4.3.6.

The drying time to reach the required relative humidity is affected by the composition and temperature of the concrete and the drying climate. Exposure of rain during transport to site (referring to prefabricated elements), or on site, delays the drying process. Johansson (2005) has studied the robustness of different concrete compositions with regard to prolonged drying times. Johansson concludes that the water to cement ration of the concrete is the most decisive parameter, by exposure of rain at early age. By low water/cement ratio (0,35-0,40) the delay is no longer than the time of exposure, whereas by a higher water/cement ratio (> 0,45) the drying time can be substantially prolonged.

Integrated life cycle design and robustness:
For the long-term owner robustness of the building is an important feature. The developments with regard to a more violent climate and other increasing risks in the society, emphasizes the value of robust construction in the life cycle perspective.
General coarse criteria relating to the whole type of building are found in the insurance classes ranging from class 1 for modern masonry or concrete frame buildings to class 4 for older wooden building frames.
For a more detailed assessment of design alternatives an experience-based, combined qualitative and quantitative system according to Sandin (1998), is envisaged. A limited number of strategic components or aspects are addressed, cf. listing in Section 5.8 and example in Chapter 6.

4.9 Lifetime usability - obsolescence

4.9.1 The relevance of lifetime usability.

Usability indicates how well the building is suited for its intended purpose. Buildings have a long life span, and the user needs are likely to change during this time. This is obvious for office and industrial buildings, but is also relevant for residential buildings. Referring to the term ‘Obsolescence’, Sarja (2003,b) states that half of all demolitions occur because the requirements of the user has changed and are no longer fulfilled by the building. Thus, it is more often the requirements on the building that change and cause the obsolescence, rather than a decreased technical performance of the building, cf. Figure 2.9.

A wide range of changes such as social, cultural, demographic, economic or environmental, may appear during the life cycle of the building. Consequently Sarja outlines an obsolescence limit state to be addressed in parallel to the traditional ultimate and serviceability limit states, cf. Section 4.1, to avoid economical and environmental damage by premature removal or renovation of a building. Sarja acknowledges that precise quantitative engineering methods are not always applicable for this limit state, but proposes a number of alternative ways to improve the basis for design decisions.

4.9.2 Design for lifetime usability

With obsolescence defined as a load, the primary response factor of the building is the flexibility for future changes. 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, such as how easily large flats can be divided into small.
- 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 physically entangled with adjacent systems.
- Reserves with regard to functional capacity of systems or structures.

There are two different approaches 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, floor height or ventilation, for more or less unknown changes in the needs of the user

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.

Saari and Heikkilä (2003) discuss the lack of well-defined design objectives with regard to flexibility and propose a classification based on three different time perspectives:

- Short: *Service flexibility*: 0-1 years. The response of a building to short-term load changes in terms of for instance mechanical load or ventilation capacity.
- Medium: *Modifiability*: 3-10 years covering movable partitions walls, load changes, adjustment of ventilation meeting foreseeable changes in needs for the users.
- Long-term: *Adaptability*: >30 years referring to adaptability in case of unknown future changes.

Adaptability for a residential building could be for example the possibility of easy changing from few large flats to several small, or for a vertical extension with additional floors or changing from residential to office use. Adaptability depends on, for instance, floor height and spans but also on the location of the building. Saari and Heikkilä define a flexibility indicator, which can be calculated for a particular space, or an entire building, and can be used as design criteria. The method suggested is primarily adapted for office buildings but could possibly be modified to suit also dwellings. Saari and Heikkilä measure flexibility by an indicator 'FlexD'. This is expressed in %, and established by subtracting, from 1, the relation between the cost to rearrange a specific area to fit a new purpose and the cost to build the corresponding new area. For example if a normal residential building, by obsolescence, could be rearranged to student flats for a cost of 700 euro/m^2 instead of producing a new building and demolishing the old, for a cost of 1500 euro/m^2 the FlexD is 1-700/1500 = 53%. Saari and Heikkilä also show how, the economical consequences by different designs with regard to flexibility, can be estimated by life cycle costing.

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, allowing freedom with regard to positioning of the interior walls, and thus freedom in respect to size of flats and rooms. Figure 4.4, shows one entire flat that is free from load carrying walls, which means that the configuration of rooms is totally flexible from a load carrying point of view. Another possibility is to increase height of the rooms in a dwelling building in order to allow for future changes in use, for example from residential to day care centre, or to office or shop.

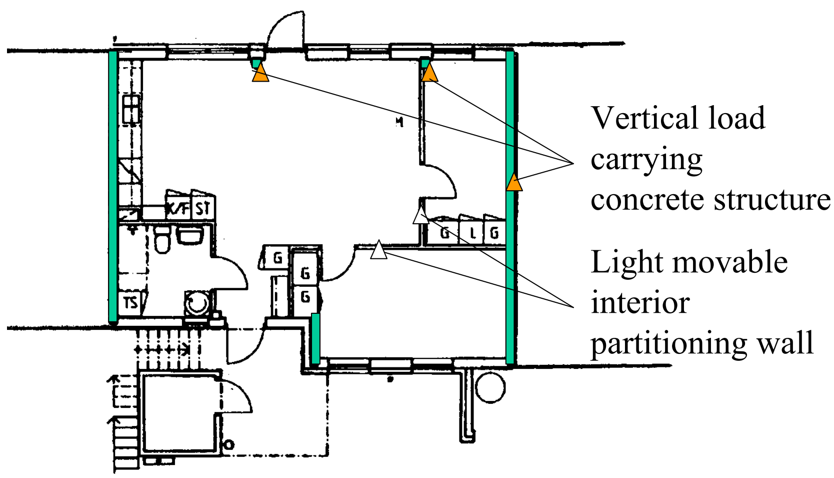


Figure 4.4 Plan of flat in the Erlandsdal project (Öberg, 2002). No load carrying structures interfere with the layout of the flat.

For the dwelling building design a general way to deal with flexibility/usability/obsolescence would be to consider and specify the flexibility systematically according to the three levels presented above. Life cycle costing can be applied to evaluate different scenarios in relation to any specific change in construction cost related to improved or restricted flexibility.

4.9.3 Concrete and lifetime usability

Concrete can contribute to lifetime usability by its high load carrying capacity. As discussed in Section 4.1, the concrete structures normally have a large inherent structural margin, that permits changes and added loads. It is also relatively inexpensive to obtain additional margins by, for instance, some extra reinforcement. The sturdiness and weight of concrete, however, makes the material less suitable for parts of the building that might need to be rearranged often, such as interior partitioning walls. Figure 4.4 is a good example of a combination of the load carrying capacity of concrete as structural frame and lightweight interior partitioning structures.

Integrated life cycle design and lifetime functionality and usability:
Lifetime functionality and usability are typical features that can be addressed by ILCD. To systemise this property, objectives can be organised in three dimension of flexibility (Saari and Heikkilä, 2003). These objectives are also addressed in Section 4.10.1.
A) Service flexibility: 0-1 years.
B) Modifiability: 3-10 years covering movable partitions walls, load changes, adjustment of ventilation meeting foreseeable changes in needs for the users
C) Long-term adaptability: 30- years referring to adaptability in case of unknown future changes.
LCC and LCA can be applied to evaluate different alternatives from economical and environmental point of view. An example on this is given in Chapter 6.
With regard to the long-term adaptability one difficulty is to establish the probability that the desire for change occurs. For an office building this probability is high while for a residential building it is not that obvious, and must therefore be considered specifically, for each project.

4.10 Architecture

Architectural quality is a very wide subject ranging from cultural and social contexts to functional and technical quality, in principle with a scope of all attributes. The ILCD concept supports architectural design by prediction of consequences related to design choices, but it is not deemed appropriate to include architectural design into the specific ILCD methodology. However, as architecture is fundamental for the quality of the building a brief overview on architecture and dwelling buildings is given in this section.

Architecture can be sorted in a quantitative, technical-functional and a qualitative dimension. Lidmar-Reinius and Björklund (1991) lists five generic criteria for architectural quality.
Four functional-technical criteria that can be quantitatively expressed:
- Generality.
- Accessibility.
- ‘Area economy’.

- Usability.

and one qualitative criteria:

- Character.

Lidmar-Reinius (1987) establishes a method to assess architectural quality with regard both to quantitative and qualitative criteria, and primarily to determine if the building fulfils the relevant building regulations. The method is applied on a representative selection of new Swedish multi-family dwelling buildings. If such a method could be applied in practice, for direct design is not known to the author. However, as feed-back tool for any project it is be possible to utilize and the study that was conducted provides a good reference.

4.10.1 Architectural quality – quantitative

The quantitative architectural requirements are typically addressed in regulations and standards. In NGB (1994) the regulated requirements on the quantitative architectural dimension in the Nordic countries are reviewed. The following items are identified, relating to the technical requirements discussed above:

- Accessibility.
- Minimum size of flat.
- Connections between rooms.
- Day-light:
    - All rooms should have daylight.
    - A flat larger than 1 room and kitchen should have daylight access from more than one direction.
- Minimum height of room.
- Specific sizes of rooms such as minimum widths.
- Furnishing possibility.
- Storage capacity.
- Technical equipment standard.
- Access to balcony or outdoor space.
- Resource use:
- Function provided/area. ('Area economy')
- Reliable materials.
- Easy cleaning surfaces.
- Adaptability:
    - A structural frame providing possibility to move interior walls or to split one flat into two smaller flats, qualified for added economical support in the previous system for public funding of residential buildings.

The system for public funding of construction of Swedish residential buildings, employed until 1990, to a large extent influenced the design of dwellings. With the society as an important economical stakeholder in the projects, it also had an interest to safeguard the quality of the buildings. If adapting the building to, the detailed and specific guidelines and standards, the investor was entitled to funding. The present planning criteria can to some extent be traced back to these funding guidelines. The criteria can be found in relevant standards such as, Swedish standards SS 914221 Building design – Housing – Furnishing sizes and SS 914222 Building design – Housing - Functional planning. However, by dismantling of the funding system, these standards have lost their normative influence on planning and design of dwelling buildings. Being the result of decades of research and experience, these standards, however, contain valuable information for the client.

4.10.2 Architectural quality - qualitative

Nylander (1998) has defined criteria for the qualitative dimension, or 'character', in a set of seven fields of properties dealing with materials and details, visual aspects, configuration of rooms etc. Nylander has later applied these criteria to assess the architectural quality of existing residential buildings, and furthermore utilised them in architectural education.

Nylander and Forshed (2004) have outlined design objectives with regard to the qualitative, or character, aspects specifically for the development of new multi-dwelling buildings for a national Swedish organisation for housing-cooperatives.

The municipal planning authorities further to the client and the architect, also to various extents, influence the exterior aesthetic appearance of a building.

4.10.3 Concrete and architecture

There are two different fields of relevance to architecture and concrete.

<u>As structural material</u>, which by load carrying capacity and formability provides freedom for open planning and shaping. Here concrete can be used as an aesthetically neutral material, hidden inside de structures, but the expression of concrete can also be a design feature.

<u>As surface material</u>. The type of structural frame is seldom a restriction regarding the choice of façade material. A building with a lightweight frame can be designed looking like a 'stone house' and vice versa. For concrete the technical possibilities are available, at reasonable cost, to provide most kinds of surface textures and colours, and the strength and formability of the material permits, in principle, unrestricted shapes. Hertzell (2002) has compiled a comprehensive handbook on architectural aspects on concrete surfaces providing examples and guidance on specification and production.

Concrete suffers from a negative social and aesthetical image. This, is primarily caused by the frequent use of precast façade elements, in social mass housing projects, see Figure 4.5. They were launched in Europe, in the post war period, to meet the great need for new dwellings. It should be noted that, in Sweden a large proportion of these mass-housing projects were not precast concrete structures, but had often aerated lightweight concrete block façades.

Figure 4.5 Early 1960s social mass-housing with prefabricated concrete elements.

The negative image cannot, however, be related to concrete as a material. The projects were the building sector's response to the ambitions of politicians and city planners, to produce a certain number of flats within a strict frame of cost and time. As a contrast, modern Swedish precast dwelling buildings are shown in Figure 4.6. Here some aesthetical possibilities are illustrated, with regard to, for instance, surfaces, textures, colours and element joints. Refer also to the cover of this book showing a contemporary precast concrete residential project in the vicinity of Stockholm, with painted sandwich façade elements.

Figure 4.6 Examples of façade designs of modern Swedish precast concrete dwelling buildings. Top left: Concrete surface similar to sandstone obtained by washing of the fresh, coloured concrete. 'The Arch of Bofill'. Stockholm, Top right: Painted elements with surface structure similar to rendering and joints used as design feature. Frösön, Jämtland: Bottom left and right 'Joint free' sandwich elements with lightweight aggregate in outer leaf. Stockholm. Also compare cover photo, showing a painted sandwich element façade.
Top left and bottom left and right with permission of Skanska Prefab AB, Malmö, Sweden.
Top right with permission of SCF Betongelement AB, Strömsund, Sweden

Integrated life cycle design and architecture

Architectural work relates to most of the attributes presented in this chapter. Also some of the aspects specifically listed in this section, such as adjustability, are addressed in relation to other attributes. ILCD can thus support architectural work. However, it was not deemed relevant to establish any specific architectural ILCD criteria.

4.11 Life cycle costs and revenues of residential buildings

The average Swede spends about 22% of the income after tax on housing (SCB, 2000) and the average flat owned by a semi-public housing company represents an asset of about 50000 Euro. Therefore, the economy of buildings has a large impact on the private as well as public economy.

In this section the life cycle economy of Swedish multi-dwelling buildings is examined by studies of statistics and a field-survey. The information is utilized in the life cycle cost module of the ILCD – toolbox, presented in Chapter 5.

By facility management accounting, the costs are usually grouped into capital costs, periodic maintenance and operating costs. The capital costs relate to the investment when the house is produced, refurbished, or bought, and to property tax. Periodic maintenance refers to the planned maintenance actions that recur with some interval greater than one year. Operating costs include the use of commodities such as energy, water and sewage, waste handling, administration and care-taking.

4.11.1 Statistics on building lifecycle costs in Sweden

The official body: Statistics Sweden, annually collects and presents data on production as well as user phase costs for dwelling buildings in Sweden. The data are distributed on type of tenure as well as geographical location. Another source for information on the user phase costs is the facilities management cost planning guide supplied by the company REPAB (2000).

The prices of electricity, district heating, oil, water and sewage, and waste disposal are benchmarked annually for all Swedish communities by EKAN (2003). A 1000 m^2, 15 flat, multi-family dwelling with defined use of utilities is the reference. This is an excellent source for cost data for LCC – calculations. The costs for the specific community can thus be inserted and utilised at the calculation.

Diagram 4.5 shows the distribution of average spent costs in Swedish multi-dwellings, of different ages, according to Statistics Sweden (SCB, 1999). The largest variation between the different age groups lies in the financial costs. This is to a large extent explained by drastically decreased public funding from 1990. Furthermore, the production of new multi-dwelling buildings after 1991 has been at a historically low level, and with an unusually large share of high standard flats.

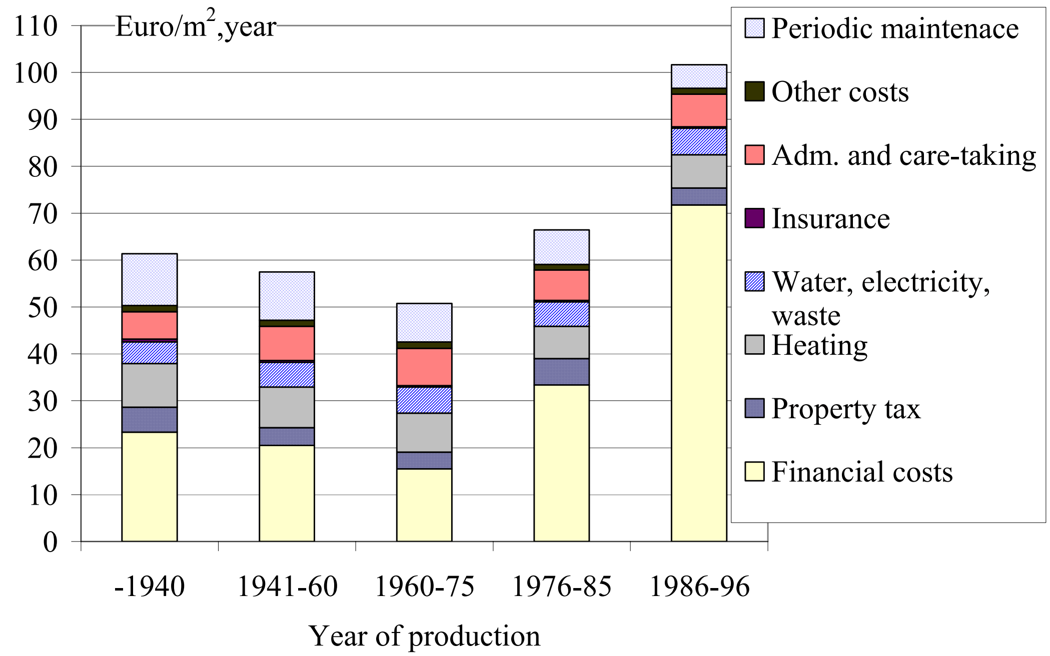


Diagram 4.5 Distribution of costs in Swedish multi-dwelling buildings during 1998 according to age (SCB, 1999).

The cost of periodic maintenance in new dwellings is about two thirds of that in the older building stock, depending on some major renovations occurring normally at the age of 30 to 50 years. These are for example exchange of elevators and plumbing. The heating cost is lower in new buildings because of gradually increased demands with regard to energy savings.

4.11.2 Case study on costs in modern Swedish multi-dwelling buildings and comparisons with relevant statistics

This case study was undertaken by Johansson and Öberg (2001).

4.11.2.1 Presentation of the buildings

Building and operating costs of four modern Swedish concrete multi-dwelling buildings were collected and analysed. The buildings were selected to represent different forms of tenure, geographical location as well as different production methods. The houses are presented in Table 4.6, Figure 4.7 and in the text below.

Figure 4.7 Buildings in case study on life cycle costs (Johansson and Öberg, 2001). Photos by the author.

Table 4.8 Summary of 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	Balanced with heat recovery
Heating	Hot water radiators	Hot water radiators	Hot water radiators	Hot water radiators
No of floors	5	5	2	4 + basement
No of flats	58	60	64	25
Usable/Gross floor area	0,74	0,74	0,85	0,65

Terränglöparen', and 'Joggaren', Lidingö

The buildings belong to two groups, each consisting of five 4 to 5-storey apartment buildings built in the vicinity of Stockholm. The project was an own development project, undertaken by a major Swedish construction company. It was completed in 1994, and formed the basis for a comparative study, with the aim to compare different aspects of cast-in-place technology with prefabrication (Paus, 1996). The ownership was transferred to housing co-operatives some years after completion, which currently is a customary procedure for new housing developments in Sweden.

Erlandsdal 1B. Svedala

Erlandsdal 1B was built for the semi-public housing company, in South Sweden. It is procured on a modified design and build contract. 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/m^2, 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 discarded 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 was used, cf. Figure 4.4, and a masonry brick façade cladding was selected instead of wood panelling, with a lower production cost.

Aspnäs 7. Frösön

'Aspnäs 7' is a privately owned single multi-dwelling block building, situated in the community of Frösön, in Northern Sweden. Further to 52 flats for rent, the building comprises a large basement floor, including parking facilities. It was procured on design and build contract and based on a type dwelling concept, developed by the precast company[9] that was responsible design and production of the building frame, including the façades.

4.11.2.2 Project costs

Project or initial costs, which also are referred to as capital cost, can be grouped into development costs and construction costs. The development costs primarily consist of expenses 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.

In Table 4.9 the total project costs for Erlandsdal and Aspnäs according to Öberg (2002), are presented in detail. Costs displayed refer to date of construction.

[9] SCF Betongelement AB, Strömsund, Sweden

It should be noted that the concrete frame in Aspnäs, which is a multi-storey precast structure with concrete façades, and contains a basement floor, constitutes a larger part of the building than the concrete frame in the two-storey Erlandsdal project. These two cases, therefore, cover the range of cost share for the structural frame, which is of interest in regard of life cycle optimisation of buildings. It should also be stressed that the buildings are different in many other respects, cf. Table 4.8, and that no conclusions with regard to cost-effectiveness between the projects should 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, and not to evaluate the production efficiency for the specific projects.

Table 4.9 Total project costs according to case study for Erlandsdal and Aspnäs.

	Erlandsdal			*Aspnäs*		
Cost category	Euro/m²	Share	Share of total	Euro/m²	Share	Share of total
Development costs						
Land cost	29	0,28	0,03	92	0,64	0,10
Design cost	18	0,17	0,02	11	0,08	0,01
Municipal connections	25	0,24	0,03	18	0,13	0,02
Other development costs	31	0,30	0,03	23	0,16	0,02
Subtotal	103			144		
VAT	13			9		
Sum development cost	**116**			**153**		
Construction costs						
Foundation	25	0,04	0,03	39	0,06	0,05
Concrete frame	71	0,10	0,09	186	0,27	0,23
Structure completion	198	0,28	0,25	112	0,16	0,14
Internal finishes etc.	139	0,20	0,17	86	0,12	0,10
Service systems	139	0,20	0,17	154	0,22	0,19
External works	69	0,10	0,09	72	0,10	0,09
Preliminaries	70	0,10	0,09	50	0,07	0,06
Subtotal	711			699		
VAT	177			175		
Sum construction cost	**888**			**874**		
Total project cost	**1004**			**1028**		

Diagram 4.6 shows the distribution of total project costs in the projects in the case study, according to the statistics (SCB, 2000) and a theoretical building according to the cost guide Bygganalys (1999). The costs accounted for in Terränglöparen and Joggaren are average costs representing three similar blocks.

The location of the project is important for development costs and in particular for the cost to acquire land. In the Stockholm area, development costs were on average 240 Euro/m², while in smaller communities the average was 170. This is one explanation for the differences in distribution between development costs and construction costs in Diagram 4.6.

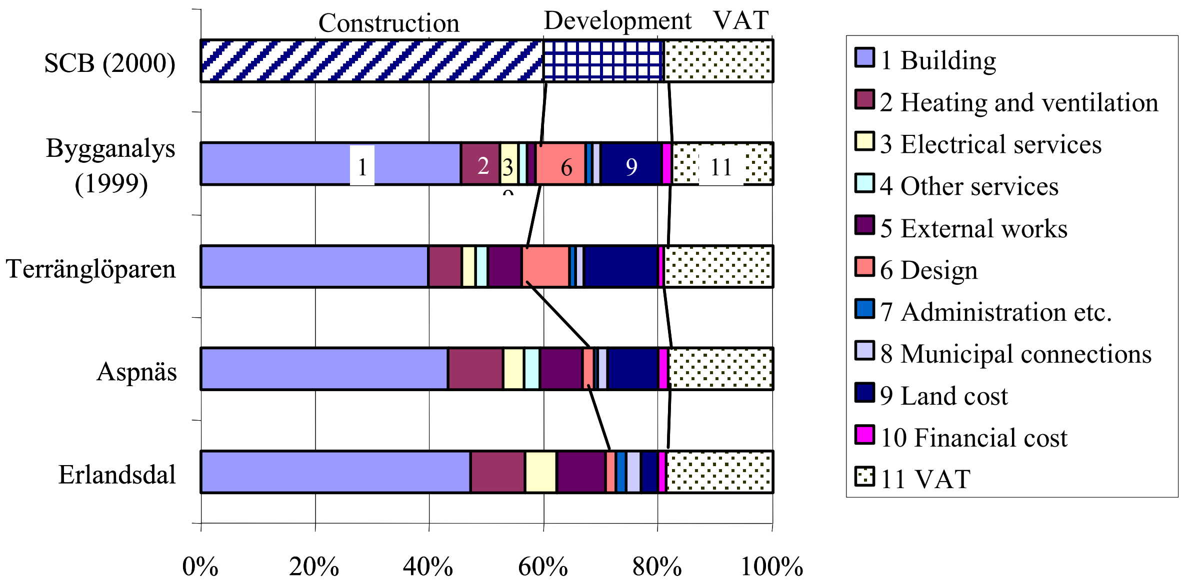


Diagram 4.6 Distribution of project costs for projects in the field study, according to the statistics (SCB, 2000) and the cost guide (Bygganalys, 1999).

4.11.2.3 Operation and management costs

<u>Municipal services</u>

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 vary significantly also irrespective of that. According to EKAN (2003) 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/m² in the city of Östersund to 27 Euro/m² in the city of Karlskrona. In communities with fewer than 15000 inhabitants the range is from 17 to 30 Euro/m². Table 4.10 shows the average municipal costs for 1998 and 1999 for the buildings in the case study, and the 1000 m² type building according to EKAN (2003). 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 common interior areas such as stairways that would require lighting. Furthermore, each flat in Erlandsdal is equipped with a washing machine instead of a common laundry room, which is why electricity for laundry is accounted for as domestic electricity in the individual flats. Finally there are no elevators.

Table 4.10 Municipal costs for case study and type building (Euro/m², 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. For instance deposition of combustible waste is not permitted in Sweden after 2002, and deposition of organic waste not after 2005.

Administration and Care-taking

Administration costs are dependent on the form of tenure, social stability of the residents, size of the housing company, and the geographical distribution of the buildings, size of the flats, and a number of 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, which directly correspond to characteristics of the materials and components chosen. In the actual case study, administration costs vary between 1 and 3 Euro/m², year and the care-taking costs range 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 concrete floors separating flats, while in the class with the highest cost these structures are all of timber. Here the cost relation is 1:2,8. 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.

4.11.2.4 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, 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.

The owner of the building must also optimise the maintenance activities over time in such a way that the deterioration of materials is controlled. 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 actual costs for periodic maintenance cannot be obtained.

4.11.3 Relevance of different cost categories for lifetime economy

The costs are to various extents dependent on the design of the building, which is indicated in Diagram 4.7, based on a case study on modern Swedish multi-dwelling buildings by Johansson and Öberg (2001). The life cycle cost were estimated as the total present value of costs with a calculation horizon of 60 years. The large variation with regard to development cost refers to differences in price of land. Note that the initial cost, comprising development and construction costs, represent 50 to 60% of the total life cycle cost by this way of calculation, and that heating and periodic maintenance are the most important user phase related costs representing more than 10% of the total cost, each.

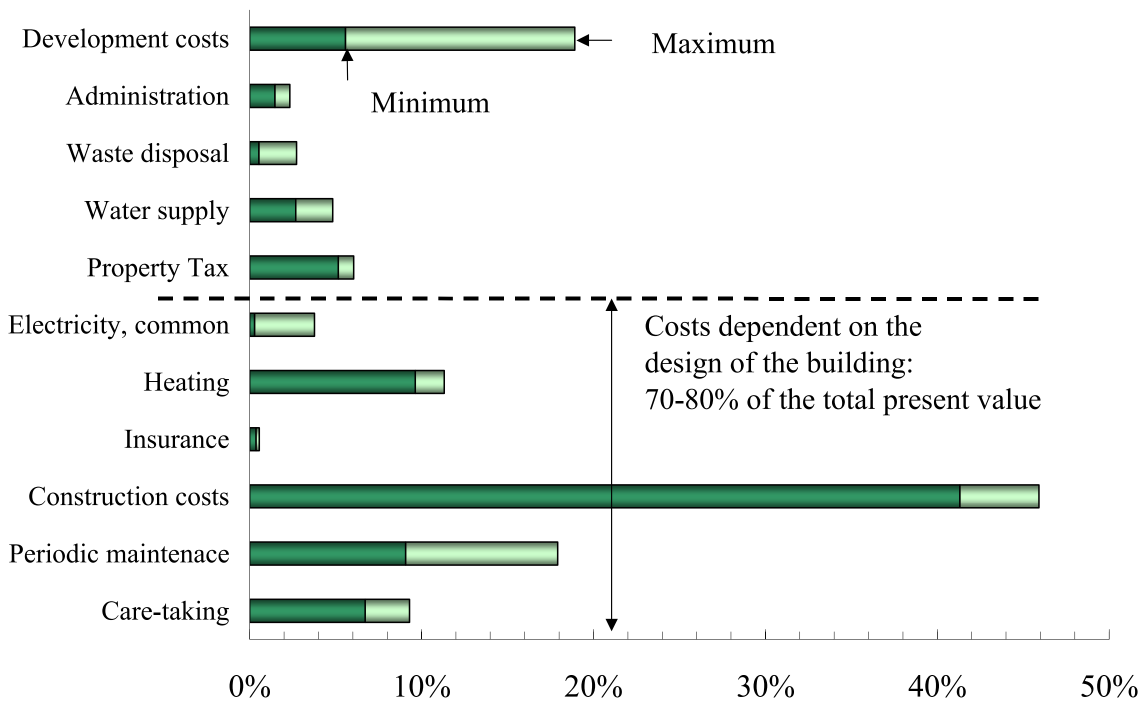


Diagram 4.7 Life cycle costs of modern Swedish multi-dwelling buildings and their dependence on the design of the building, according to Johansson and Öberg (2001).

The costs are to a large extent dependent on the aptitude of the designed building in relation to the functional requirements discussed above. For example, the relation between gross building area, or volume, and area for rent is crucial with regard to both economy and environment. This ‘planning efficiency’ criterion is covered by attributes such as architecture and functionality/usability discussed above.

4.11.4 Revenues of residential buildings

The whole life economy of the building is dependent also on revenues, which must also be included in the planning. For example one critical aspect is the size of each flat in relation to the rental policy. Every flat needs a similar set of basic, but comparatively expensive facilities, both with regard to initial and operating costs, such as kitchen and bathroom. As the cost for these facilities is distributed on the area of the flat, the cost per square meter is highly affected. Many Swedish housing companies establish the rent directly in relation to size of the flat. In such a case a large flat is more economical than a small. There are also socio-political aspects involved in this context. Specific subsidiaries for production of small flats are currently available in Sweden. Political regulations on the maximum allowable rent also influence the whole life economy of residential buildings.

4.11.5 Concrete and the economy of residential buildings

The building materials influence the economy of a building through the production cost, to various extents through operating costs, and by the final disposal cost, or second hand value. By life cycle cost estimations of different alternatives, it is possible to utilise a material, for example concrete, in the most efficient way. Reinforced concrete can with good precision be tailored to fit a wide range of functional performance requirements in terms of strength and durability. Normal concrete compressive strength can, for instance, be varied with a factor 1 to 5 within range of the European concrete standard, and by using the effect of reinforcement even larger differences can be obtained. It is therefore possible to find economical concrete solutions to the structural frame. A general observation by the author is that the effectiveness of concrete increases with the specific load. This is one explanation why, in Sweden, the majority of multi-dwelling buildings have concrete frames, while most detached houses have timber frames.

Integrated life cycle design and economy of buildings

Economy is a key component of ILCD and addressed as such throughout this work. One point that can be noted is that from the client perspective, the economy of a building can be regarded as:

- The resulting sum of predicted total life cycle costs and profits, which should be optimised or a
- a design criterion, in principle like any other criterion, whereby a target value, for example for rent and revenues, can be prescribed.

4.12 Environmental burdens of buildings

This section deals with the global and local environmental aspects on buildings, including the use of materials and energy resources. Indoor environment is discussed in Section 4.3, and work environment is not addressed in this work.

4.12.1 Buildings and the global environment

Within the EU, 40% of both total energy consumption and material use refer to the built environment, EU (2002). This implies a great general environmental interest in the sector. The Swedish national committee on the environmental consequences of the building sector (BK, 2001), ranked energy consumption during the user phase as the most severe environmental burden related to houses. Materials use were placed second, elimination of hazardous substances in third, and noise protection the fourth, in order.

The general method to estimate environmental performance of a product is LCA. This methodology and its applicability in the building sector are discussed in Section 2.5.

From the designers perspective the environmental burden, analogous with life cycle costs, of a building can be regarded as:

i. A consequence of how the building is estimated to perform with regard to energy use, durability etc. The environmental burden can be assessed for the design alternatives and taken into account by decision-making.
ii. A design criterion, in principle like any other, whereby a target value or a class can be prescribed. Erlandsson (2004) has proposed a classification in three levels: A Sustainable, B Environmentally sound and C, Acceptable. C represents the current praxis and A fulfils long-term environmental goals. Erlandsson points out that the A class implies ecological sustainability and does not address the economical and social dimensions of sustainability.

4.12.2 Energy use

Energy is used through all life cycle phases from the extraction of raw materials to demolition and recycling. The relation between different phases in the life cycle, regarding energy use is presented in Table 4.11, which shows results from two studies, confirming that the user phase is dominant. Normally, multi-family residential buildings are expected to last longer than 50 years, which emphasises the user phase even more.

Table 4.11 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), for a similar theoretical building according to (B) Björklund et al (1996) and for typical U.S residential building (Webster, 2004).

	Adalberth		B	USA
Life cycle phase	kWh/m²	Share	kWh/m²	kWh/m²
Production of materials and components	820	10%	340	700
Transports of materials and components	30			
Building site	120		30	
Use (heating, hot-water, light, other electricity)	7500	85%	7640	11800
Maintenance and repair	410	5%	60	250
Demolition	< 10	<1%	14	-
Demolition material transport	20		8*	-

** 30 km truck transport of approximately 1000 kg construction waste per m² gives 8 kWh/m².*

The discrepancy between the studies presented in Table 4.11, with regard to energy used for production and maintenance is due to the fact that Björklund only considers materials and components related to a part of the building and only materials constituting frame and climate shell. Roof, foundation, technical service systems, fittings etc. are thus left out. It is therefore irrelevant to express Björklunds figures in terms of share, to be compared with the user phase.

Energy consumption during the use of a building is described in Section 4.6. The energy use for the production of a building is distributed over extraction of raw materials, transport of raw materials, 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%.

Adalberth (2000, paper 3, p 7), examined four different existing modern multi dwelling buildings, comprising between 6 and 16 flats. The study included 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, 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 life cycle perspective, here restricted to 50 years, with an operational phase requiring approximately 7500 kWh/m^2, the difference between the energy use regarding the production phase, of structures based on very different materials and systems, is small.

Several types of environmental stressors relate to energy consumption such as:

- Emissions by combustion leading to
  - global problems such as global warming and stratospheric ozone depletion and
  - regional and local problems such as acidification and eutrophication.
- Disturbance of landscape and ecosystems related to hydro- and windpower facilities.
- Human health risks related to the
  - production, use and final disposal of radioactive material for nuclear power and the
  - carcinogenic exhaust gases from small scale combustion.

No energy sources currently used, in large scale, are exempt from environmental disadvantages. A residential building usually exists over a long period of time during which the technical energy supply systems and the available energy sources change. One difficulty with regard to the energy supply and installations management is the type and amount of primary energy consumed in relation to the effective energy use. These factors are sometimes difficult to analyse, and likely to change over the building life cycle, with effects, on the environmental performance, out of the control of the client.

An alternative method to determine the efficiency of energy sources and energy supply systems is measuring the consumption of exergy. Exergy defines the level of mechanical work that can be obtained from an energy carrier. Electricity has high exergy, while, for instance, warm water from a solar panel has low exergy. Typically a low temperature heat source, operating with a small difference between heating media and the tempered air, has low exergy. Low exergy systems are preferable from the environmental point of view. Schmidt (2004) outlines a method for exergy optimisation. Energy source and energy carrier can be selected according to the specific need and the energy flow may be used several times within a building, even though its 'quality' or exergy is decreased by each step.

Considering the aspects discussed above the author proposes the following order of priority with regard to energy design and management of residential buildings:

1. The building should require a minimum of supplied energy. A well-insulated climate shell, consideration of the external and internal heat gains and using daylight for lighting. Artificial cooling should be avoided by passive cooling strategies.
2. Heating systems should be flexible with regard to energy source.
3. Low exergy systems is preferred.
4. HVAC system and other installations that are optimised by for instance heat pumps, heat recovery of exhaust ventilation and sewage water should be used. Low energy appliances should be used.
5. A 'green' energy supplier is preferred.

4.12.3 Material use

The European construction sector accounts for a large share of the total flow of raw materials. For infrastructure construction this was defined as the most important environmental burden according to BK (2001), and for houses the second, only to energy use.

To optimize a supply chain with regard to material flows, a combination of aspects need to be considered such as:

- The nature of the raw materials used. These can from the ecocycle perspective be grouped into:
  - Non-renewable virgin materials with limited availability.
  - Non-renewable virgin materials abundantly available.
  - Renewable materials.
  - Recycled materials.
- The generation of waste during manufacture, transport and use
- The functional quality of the product is a crucial aspect in case the raw material used will in some way influence the function of the product. For

instance, if the choice of raw material effects the longevity or need of maintenance.
- The expected lifetime of the product, which is indicated in Figure 3.5. For an item with shorter lifetime it is more important to emphasize the recycling aspect than for an item with longer lifetime.
- The disposal of the product at the end of the life cycle. If the product can be reused, recycled as raw material, used as fuel or need to be land filled.

Sarja (2002) proposes a system to estimate the recycling efficiency by dividing the building into four system levels; building, assembly, component and material. Each level has a basic recycling factor ranging from 0,6 for the building to 0,2 for material. The basic factor is adjusted with regard to separability, moveability and re-integrability to a final value ranging from 0,9 to 0,0.

4.12.4 Concrete and the environment

4.12.4.1 Concrete and the environment – energy use and emissions by production

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, including the base report on cement and concrete by Vold and Rönning (1995). Furthermore, LCA tools including databases were introduced for product development and for the compilation of quantitative environmental product declarations for cement and concrete. The studies show, that emissions to air of CO_2, NO_x, SO_2, and use of fossil fuels and electricity as energy resources, represent 90 to 95 % of the total environmental burden from cement, as well as from concrete production. Three different environmental impact valuation models, cf. Section 2.5.2, were applied, in order to verify the results. The emissions primarily relate to combustion of fuels by the, high temperature, ‘calcination’ process, whereby limestone is transformed to cement ‘clinker’, and furthermore to transportation of raw materials and concrete. CO_2 is released to air in the chemical reaction when limestone is transferred to cement clinker. The concrete absorbs this ‘chemical’ part of the CO_2 emission again over time, in the process of carbonation.

Environmental improvement of the cement production is achieved, for instance by cleaning of exhaust gases, and by exchanging a part of the cement clinker with mineral additions, such as finely ground limestone. Also some waste materials, such as fly ash or slag, may be used to substitute some part of the clinker in certain types of cement. Finally, CO_2-neutral waste fuels, such as car tires, bone meal and sewage sludge, can replace the fossil fuels by clinker production.

Diagram 4.8 displays the distribution of energy use for the production of a typical cast in place reinforced concrete structure, calculated according to the LCA model presented in Section 5.12.2, with data according to Annex 5.F and Table 6.9, alternative 'BEST'. Note that a substantial part of the cement (20-25%) and steel production energy use refers to waste fuels. In magnitude of energy required for production in ralation to the user phase, is pointed out by the bar below the pie chart. The energy required to produce 1 m^2 of building frame, 350-450 kWh, c.f Table 4.11, is in the same order as the energy consumed for operation of 1 m^2 of a multi-dwelling building, during 2-3 years.

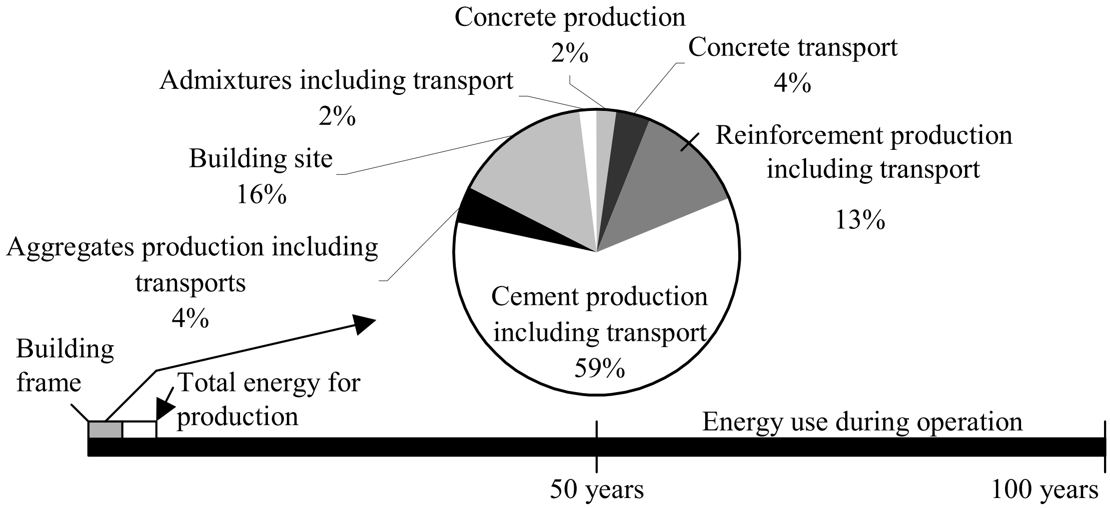


Diagram 4.8 Distribution of energy use for the production of reinforced concrete and relation between production and user phase energy consumption.

The total environmental burden of concrete increases with the cement content, cf. Diagram 4.9. If an optimal environmental performance is pursued, it is important, however, to take into consideration that the basic functional quality aspects of concrete, such as strength and durability, also increase with the cement content. With respect to 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, Diagram 4.9 shows the environmental impact on concrete elements according to LCA, using the 'Environmental theme' weighting method (Hejungs et al, 1992). The wall element has a C30/37[10] concrete with plain reinforcement. The high strength beam has a C80/95 concrete and pretensioned reinforcement. Looking strictly at the environmental burden from production, the low-grade wall element is advantageous. With a functional parameter taken into account, in this case the concrete compressive strength, the high strength beam that requires a larger production effort, is still environmentally preferable.

[10] Concrete grade expressed in characteristic cylinder/cube strength according to European concrete standard

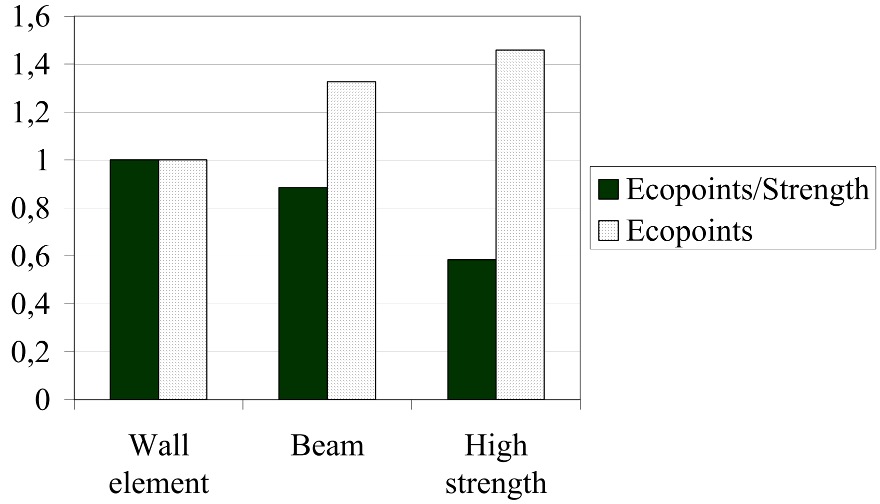


Diagram 4.9 Environmental burdens of different concrete products according to the Effect Category weighting method (Hejungs et al, 1992) with and without taking functional performance expressed as compressive strength, into account. Wall: C30/37, Beam: C50/60 and High strength beam: C80/95 (Öberg, 2000).

A C50/60 concrete requires approximately 100 kg of cement more per m^3 concrete than the C30/37. The corresponding increase of energy use is approximately 30 kWh of fossil energy, and 10 kWh of electricity per m^2 for a 250 mm concrete slab. This represents, for example, about 0,4% of the life cycle energy use of one m^2, of a multi-dwelling building, cf. Table 4.11.

Reinforced concrete is a material with relatively low embodied energy. This is particularly pronounced if its functional performance and durability is effectively utilised. One concrete column with a square cross section 300x300 mm, and a length of 3 m, weighs 660 kg, and carries 1500 kN or 150 tons of working load. The inherent energy from cradle to finished structure is approximately 225 kWh. A typical 240 mm reinforced concrete floor slab, that spans 7 to 14 meters depending on bearing system, in a residential building, weighs 590 kg/m^2. It has an inherent energy from cradle to finished structure of about 155 kWh/m^2.

4.12.4.2 Concrete and the environment – Materials aspects

Concrete is primarily composed of mineral materials cf. Diagram 4.10, which displays the constituents of a typical concrete for house construction in Sweden. The self-weight of reinforced concrete is 2400 to 2450 kg/m^3. Admixtures are normally polymers like napthalens or melamines, introduced to enhance workability of the fresh concrete, or to secure frost resistance for concrete structures, that are exposed to freeze-thaw and wetting.

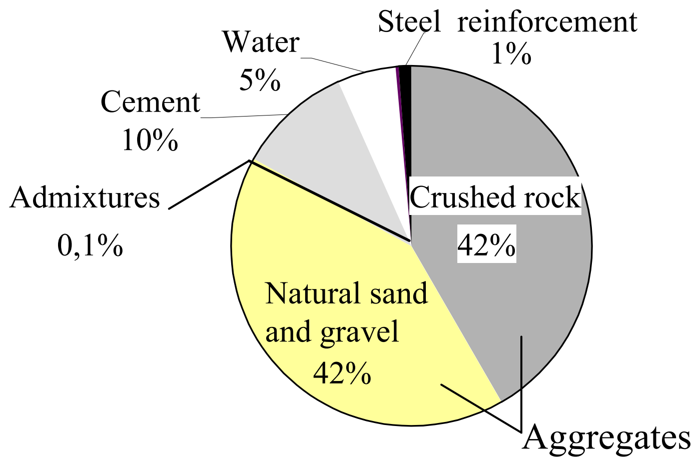


Diagram 4.10 Composition by weight of a typical concrete for house construction.

Referring to the characterisation of materials above the constituents of concrete can be classified as abundantly available, non-renewable, virgin materials, or in case recycled concrete is used as aggregate – recycled material. The availability of natural sand and gravel in Sweden is, however, in certain areas restricted, in order to safeguard the supply of drinking water. Therefore, the proportion of crushed rock aggregates is increasing. It has been shown that concrete can be produced with 100% crushed aggregates. In 2004, the relation between crushed and natural aggregates was roughly 50 to 50% (Sandahl, 2004). Johansson (1997) presents practical guidelines on the characterization of raw material and composition of concrete with crushed aggregates.

4.12.4.3 Recycling of concrete

Recycling of fresh waste concrete is usually done at the concrete plant, where water and solid materials are separated for use in new concrete. The total amount of fresh waste concrete is about 3% of the production (Björklund et al, 1996).

Concrete from demolished buildings or hardened production waste, is crushed and the reinforcement is separated, cf. Figure 4.8. Crushed concrete can be used to substitute virgin aggregates by ground construction or in new concrete. The scrap reinforcement is recycled in steel production.

Boverket (1999,b) provides guidelines for the use of crushed concrete as aggregates in new concrete.

Figure 4.8 Recycling of hardened concrete. After coarse crushing the reinforcement is separated magnetically (rack to the left) and then the material is further crushed (right) to the desired particle size. Photo by the author.

Recycled materials, for example crushed concrete, must not release any hazardous substances to the ambient. Gustavsson (2004) reviews the total content, and leaching characteristics, of hazardous substances from concrete, cf. Diagram 4.10, and concludes that:

- Cement and aggregates contain the same types and concentrations of substances that are found in natural rocks and soils. For cement this relates to the limestone used as raw material.
- Admixtures are since 1997 certified with regard to the environment including human health and ecological risks with the EFCA[11]-seal of *Environmental Quality for Concrete Admixtures*. Gustavsson points out that risk assessment of concrete admixtures is relatively uncomplicated, in comparison with many other building materials, as they contain only a small number, as well as small amounts of chemicals and their properties are well known.

Concrete from for example industrial applications can be tested with regard to risks for leaching according methods defined by Dutch national standards NEN 7345 and NEN 7341 (NEN, 1995). By the methods any contaminations can be tracked and thus the risk for hazardous leaching, can be eliminated. A general study on concrete and leaching is presented in the report by CEN (1999).

[11] European Federation of Concrete Admixtures Associations

Integrated life cycle design and environmental aspects of buildings

Like economy, environment is a key component of ILCD and addressed as such throughout this work. From the designers perspective the environmental burden of a building can be regarded as a

- consequence of how the building is estimated to perform with regard to energy use, durability etc. The environmental burden can be assessed for the design alternatives and taken into account by decision-making or a
- design criterion, in principle like any other whereby a target value or a class can be prescribed.

Erlandsson (2004) has proposed a classification in three levels: A Sustainable, B Environmentally sound and C, Acceptable. C represents the current praxis and A fulfils long-term environmental goals. Erlandsson points out that the A class implies ecological sustainability and does not address the economical and social dimensions of sustainability.

4.13 Concluding remarks on attributes of dwelling buildings

A building must respond to a number of different requirements, by the assembled performance of its properties and characteristics, here referred to as attributes.

Attributes related to safety or health, are safeguarded by unconditional requirements stated in regulations. Most, but not all, of the criteria of this nature, are in Europe based on the essential requirements of the Construction Products Directive, '*CPD*'. There are also aspects treated in national normative or informative guidelines such as access to buildings by the disabled, usability, environmental performance or work environment. Other important functional attributes, for instance comfort, social aspects or flexibility, are optional for the client. The regulative requirements are also optional in the sense that, better quality than the minimum threshold may be ordered by the client.

The selection and analysis of attributes in this chapter is, by no means, claimed to be the only way of defining requirements on buildings. Some of the attributes are partly redundant, such as energy use and environmental burden. In other cases it is difficult to draw a distinct line between aspects, for example, robustness, mechanical resistance and durability. It is envisaged that a client may want to establish a modified list. The ILCD model developed in this research work is fully open for that.

Costs and the environmental burden can be treated as consequences depending on the functional quality ambitions, and of how optimal the construction is in relation to these. Economy and environmental performance can, however, also be targeted and thus viewed in line with the functional criteria.

The view on environmental burdens from buildings, likewise from other products or services, is in a regulative transition period. Legislative restrictions and/or increased taxation according to the 'polluter pays' principle are step by step introduced, for example on energy consumption or disposal of waste.

In Figure 4.9, the attributes are listed, and their interaction is indicated. This illustrates the complexity of functional interaction, and hence the importance of a holistic approach to design.

	Mechanical resistance….	Safety in case of fire	Hygiene, health …..	Safety in use	Acoustics	Energy use	Durability	Robustness	Lifetime usability	Architecture	Economy (life cycle cost)	Environment load
Mechanical resistance / stability												
Safety in case of fire	+											
Hygiene, health (indoor climate)	O	O										
Safety in use	+	+	O									
Acoustics	+-	+	+	O								
Energy use	+	+	+-	O	+-							
Durability	+	+	+	+	O	+						
Robustness	+	+	+	+	+-	+-	+					
Lifetime usability	+-	+-	+-	O	-	+	+	+				
Architecture	O	-	O	-	-	+	+	O	+-			
Life cycle cost	+-	-	+-	O	+-	+	+-	+	+	+-		
Environmental burden	+-	+-	-	O	-	+	+	+	+-	-	+-	

-: Improvement of one => impairment of the other.

O: No significant correlation

+: Improvement of one => improvement of the other

+-: Can work either way

Figure 4.9 Tentative matrix of fundamental attributes and their interaction.

As indicated in Figure 4.9, requirements may be contradictory, or coincide from a technical or stakeholder point of view. For example, high energy efficiency is of public environmental and energy supply interest, but it is also valuable for the client with as it decreased operational costs. Lowering temperatures and decreasing ventilation is one way to achieve energy efficiency. However, then a conflict with the indoor environment occurs. Basic prerequisites to deal with these correlations are the understanding and acknowledgment of the life cycle perspective, the interaction between attributes and how they relate to the design of the building and its service systems. ILCD brings light to these relationships.

5 INTEGRATED LIFE CYCLE DESIGN TOOL

The primary objective of this thesis is to advance the application of ILCD in practice. To this end a pilot model for simplified ILCD toolbox was developed. Its organisation, contents and verification are presented in this chapter, which is organised in principle according to the listing of attributes in Chapter 4.

ILCD comprises a number of different methodologies and tools as discussed in Chapters 2 and 3. There are both the traditional design tools, and some additional methodologies that are relatively new, at least for the building sector cf. Fig. 2.5.

The methods can be individually applied, but there are often connections between them with regard to data, why it was deemed practical to establish a pilot 'box of tools'. The work focuses on the specific methods in ILCD. Therefore, the traditional design instruments and also some of the attributes tabled in Chapter 4 are not, or only by pre-design tools, included in the ILCD model.

It was the aim to interpret, test and exploit the principles and framework of ILCD. The pilot toolbox and the results from its application should indicate the potential benefits of ILCD and serve as an idea, concept and possible base for subsequent development with regard to organisation of computing tools and data. The verification and application examples deal with concrete multi-dwelling buildings, but the methods are fully general and open.

The following criteria were defined for the toolbox:

- It should be simple enough to use to be applicable in ordinary projects.
- It should be potent enough to reveal the expected benefit of ILCD.
- It should address the relevant attributes discussed in Chapter 4.
- The computation accuracy should follow the progressive increase in detail level in the design process, from early planning to production drawing.
- The results should be reliable.
- It should allow evaluation of alternative designs and scenarios in an efficient way.
- It should be open and general to allow full transparency, future extensions and further detailing.
- It should cover all the steps of ILCD, presented in Figure 3.3.
- Where possible spreadsheets should be used.

The organisation of the pilot toolbox is presented in Figure 5.1.

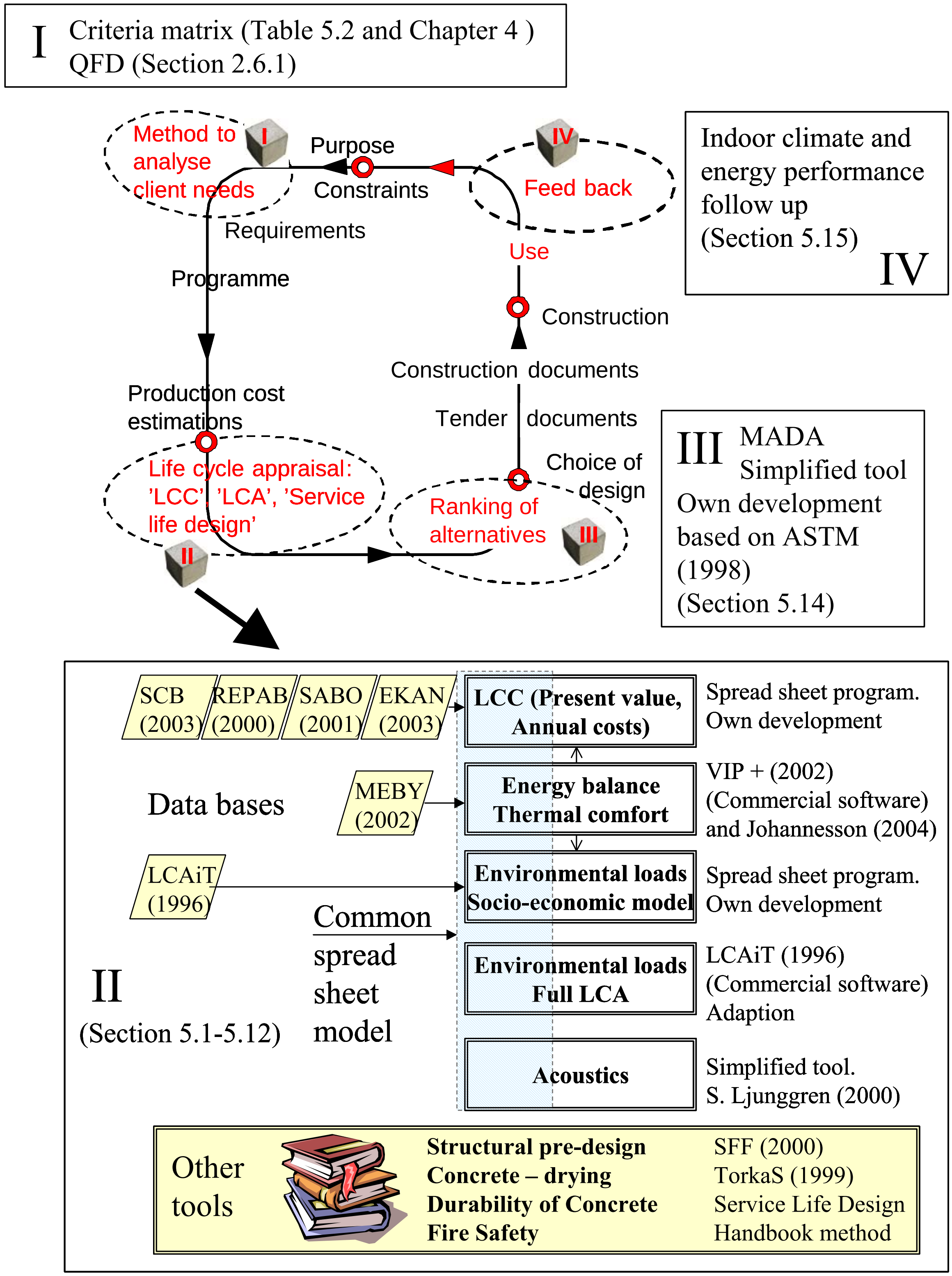


Figure 5.1 Organization of pilot ILCD model with references to specific routines and positions in the building process.

5.1 Mechanical resistance

For structural design the pre-design tool by SFF (2000), is applied for cast in place concrete, and the handbook method according to BE (2001,a) is used for precast concrete floor elements.

The SFF tool provides interactive pre-design for three different concrete grades with plain as well as post-tensioned reinforcement. Five different structural flooring systems, walls and columns can be modeled. These comprises both the traditional dwelling slab block system as well as the column slab concept, earlier more common for office buildings, cf. Annex 4.A. Both the ultimate limit and the serviceability limit states are included. Design criteria and loadings are according to Swedish regulations.

The BE handbook comprises pre-design of massive floor slabs as well as hollow core slabs, both for the ultimate limit and the serviceability limit states.

5.2 Fire safety

For fire safety design the Eurocode 2 (EC2, 2001) and the handbook method according to BE (2001,b) are utilized. The handbook provides tables with the required concrete cover to reinforcement for slabs and walls, for fire resistance classes, ranging from R 30 to R 180, cf. Section 4.2.1, and utilization of the load carrying capacity from 40 to 100%. For beams and columns detailed diagrams on temperature development in different cross-sections are available.

5.3 Indoor climate

5.3.1 Indoor climate - thermal comfort

In Section 4.3.4 thermal comfort in residential buildings is discussed. It is concluded that new building techniques sometimes result in a less robust indoor climate. This implies that increased attention to this is required from the designers. The collaboration between the architect, structural designer, heating and ventilation specialists on these aspects becomes more crucial. Computing tools that can cover both indoor temperatures and the energy performance is one logical solution. From the processing capacity point of view, this can be accomplished today also on personal computers. However, the amount of input data required, makes that approach impractical for a general case. For a residential building with moderate window areas, sufficient accuracy can be achieved with, for example, the VIP+ programme, that is presented in Section 5.6. For the general case, a programme such as BRIS (2000) or TeknoSim 2000 (Lindab, 2000) can be applied.

VIP+ was selected as the base to estimate thermal comfort. The standard output from a programme run is the energy balance list according to Table 5.1. This balance can be displayed for an arbitrary time span reaching from one year according to the example in Table 5.1, down to the one-hour computing time step the programme operates with. However, VIP+ also computes temperatures of the building frame and the indoor air. Therefore the effect of thermal storage can be examined in detail. The output is compiled in text format files, which are tailored by the user. Some special routines to transfer data from the VIP+ output format to Windows spread sheet tools have been developed by the author, to analyse and demonstrate the indoor temperatures. An example of this is shown in Diagram 5.1, which is taken from one of the projects examined in Chapter 7.

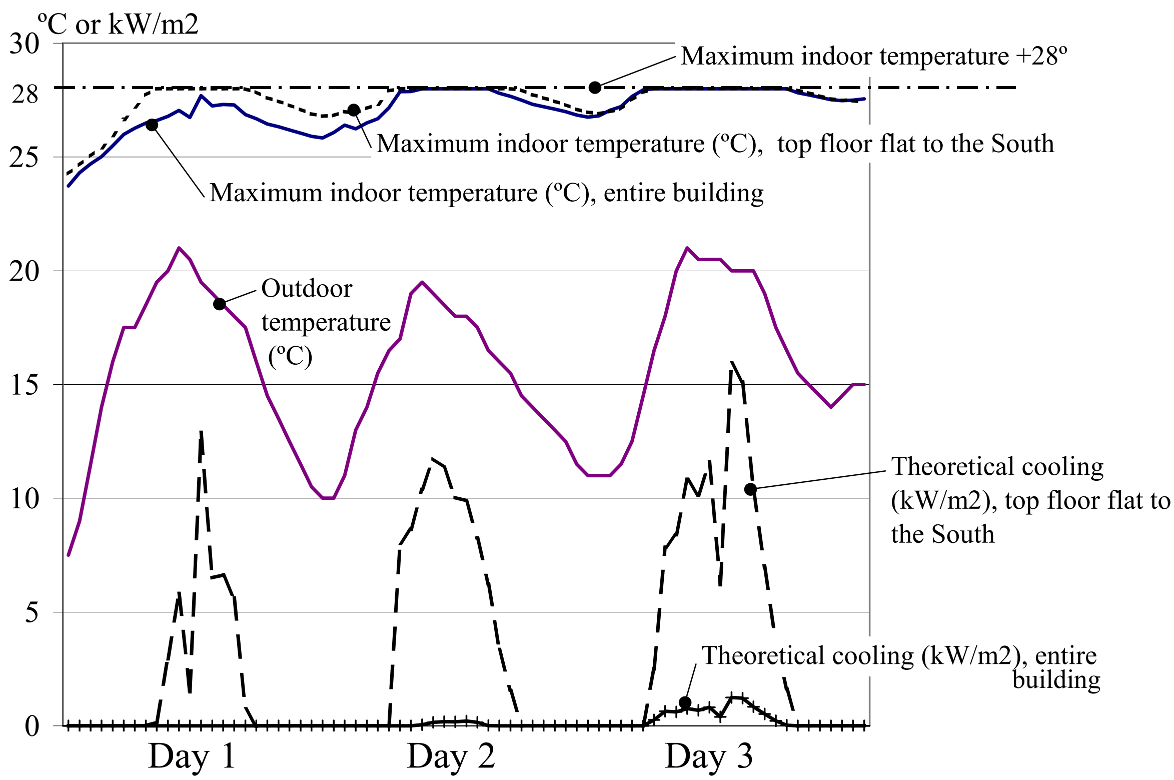


Diagram 5.1 Sequence of 3 consecutive days in June showing indoor temperatures and the cooling effect required to maintain a maximum indoor temperature of +28ºC, for a specific solar exposed flat and the entire building. Calculation by VIP+(2000)

The programme user defines the minimum and maximum allowed indoor temperatures. Swedish multi-dwelling buildings are normally heated from September to May, starting and ending with specific dates dependent on geographical location. The average indoor temperature during the heating seasons is typically near 22ºC in Swedish multi-dwelling buildings (Engvall and Norrby, 1992). This is the indoor temperature used in the calculations in Chapters 6 and 7. In order to obtain realistic results of the calculations during periods with excess temperatures, the computations should also be given a maximum indoor temperature. This reflects that in reality the ventilation then is boosted for instance by opening windows, or in case of air conditioning, the indoor air is cooled. The programme deals with this by calculating the theoretical energy requirement for this cooling to avoid temperatures higher than the defined maximum temperature. Diagram 5.1 illustrates how VIP+ operates with regard to maximum indoor temperatures. Note that when the maximum temperature is reached cooling starts.

The example refers to example D in Chapter 7. It shows the difference with regard to indoor temperature, and theoretical cooling requirements, for one flat that is highly exposed to solar radiation, in comparison with the average situation for the entire building. Diagram 5.1 indicates the possibilities for thermal analysis provided by the VIP+ (2000), included in the ILCD toolbox. It should however be noted that the programme primarily was developed as an energy balance tool, c.f. Section 5.6. Therefore, this type of calculation requires experienced users and some cumbersome exercises, to transfer the VIP+ results to spread sheets. For the general case the theoretical annual requirement for cooling, cf. Table 5.1, or the number of days per year, with indoor temperatures above the comfort threshold, are applied as indicators of thermal comfort, by application of the toolbox.

Air quality
Air quality is here controlled by ventilation rates according to the CEN (2004) classification. A higher ventilation rate will result in somewhat higher energy consumption, particularly if there is no heat recovery on the exhaust air.

A classification of self-emission rates from materials is envisaged in Section 4.3.3. Since this work primarily relates to the concrete building frame, self-emissions have not been specifically addressed in the application examples, while concrete is a low-emitting material, according to both of the classification systems that were presented.

To avoid the risk of emissions from bonded flooring systems, due to insufficient drying of concrete, the drying time is predicted by the TorkaS 2.0 (2002) programme. With this tool the relative humidity in a concrete slab at a standardised measuring depth, 20% of the thickness of the slab below the surface, is predicted as a function of time, concrete composition, thickness of slab and drying climate. TorkaS enables selection of the optimal concrete quality in relation to the required RH by application of the carpet, and thickness of slab.

5.4 Safety in use

The handbook method SSFN (1994) was applied with regard to housebreaking.

5.5 Acoustic design

Ljungren (2000) has developed a computer tool in the 'The Concrete Bank' (SFF, 2000) for the Swedish Ready Mixed Concrete Association. This is specifically developed for approximate acoustical evaluation of typical concrete building frames such as traditional dwelling slab block frame as well as column-slab frames, cf. Annex 4.A. Diagrams 5.2 and 5.3 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.

$$R_{wv}=53,2+35*LOG(h/0,16)-10*LOG(a/16)+10*LOG(w/12)-2,5+0,5-s*1-f_1*2 \qquad (5.1)$$

$$R_w =54,1+35*LOG((h-0,02)/0,16)-10*LOG(\sqrt{a}*H/16)+10*LOG(w/12)-2,5- f_1 \qquad (5.2)$$

$$L = 52-Rv+3(7- f_2)+56 \qquad (5.3)$$

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

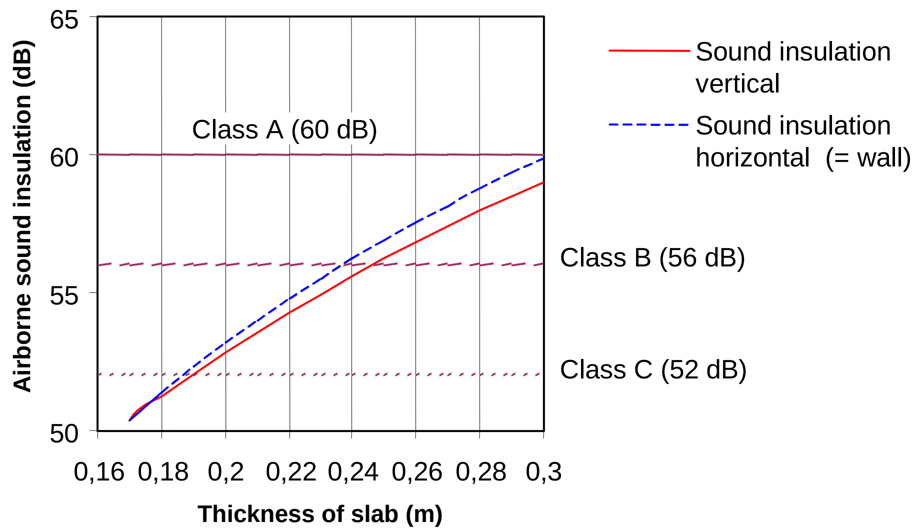


Diagram 5.2 Airborn sound reduction index for a concrete slab block frame, cf. Annex 4.A. Thickness of walls separating flats should be as slab minus 40 mm.

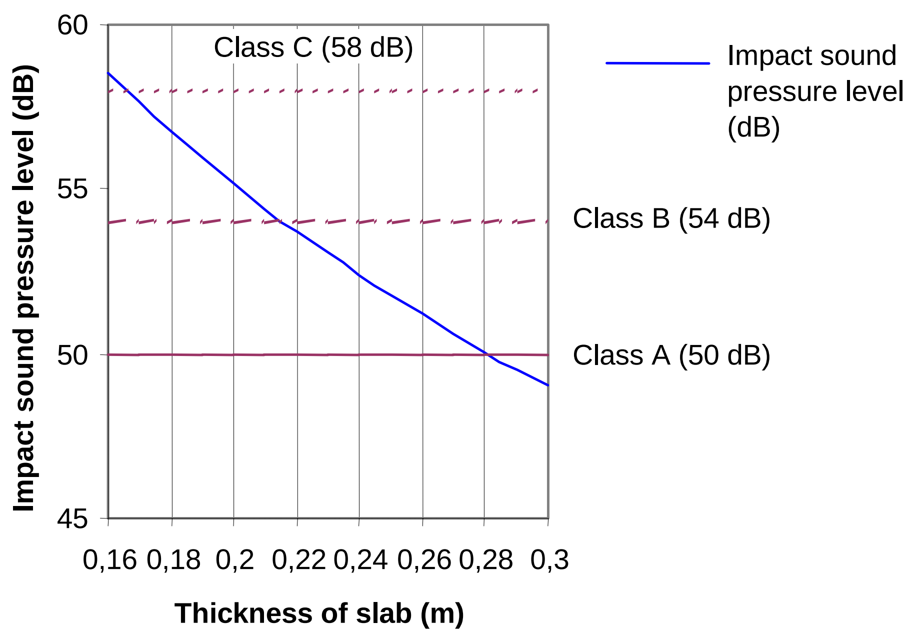


Diagram 5.3 Impact sound pressure for a concrete slab block frame.

In the example calculated in Diagrams 5.2 and 5.3, 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 = 20 m^2, width of building 10 m.

The column slab type of structure, cf. Annex 4.A1, is very advantageous with regard both to airborne and impact sound insulation. The algorithm for airborne sound reduction index through a floor in a column slab structure, corresponding to (5.1), for the slab block structure above is, according to Ljunggren (2000):

$$R_{wv} = 63{,}5+35*LOG(h/0{,}16)-5*LOG(a/16)+5*LOG(tf/600)-f_1*2-2{,}5 \qquad (5.4)$$

where

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

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

This simplified tool is very easy to use and covers a wide range of geometrical alternatives. It was deemed to be a sufficient acoustic indicator for the ILCD toolbox for pre-design. One shortcoming, in its present version, is that sound insulation towards the outside cannot be studied. An alternative calculation tool, which could be considered for future development of the toolbox, is the BASTIAN programme discussed in Section 4.5. This programme allows more degrees of freedom and also more precise estimations.

5.6 Energy balance calculations

5.6.1 Overview and selection of methods

The energy balance of a building, and the related aspect of thermal comfort, are important lifetime quality factors that need to be addressed, early in the design process. Life cycle costs, environmental and functional performance all relate to the energy balance of a building.

Traditionally, the energy related design of the climate shell is done by the architect and structural engineer, and is primarily focused on the average U-value of the climate shell. Since the EP approach was introduced in Sweden, compare Section 4.6, it has also become possible to make trade offs between U-values and other energy properties, such as improved air tightness, thermal storage, or any heat pumps or systems for heat recovery applied in the particular project.

In a review by Bergsten (2001) on commercially available energy balance programmes in Sweden in 2001, a total of 12 programmes where accounted for, ranging from simple shareware tools, providing crude estimates for single-family house applications, to customized versions of advanced university programmes. Energy balance calculation programmes can be grouped into dynamic, semi-dynamic and steady state.

Steady state programmes work in principle like hand calculations. Their main advantage is that the computation effort is very small since they do not apply any thermo-dynamical algorithms, and the time resolution is at least a whole 24-hour period. Indoor and outdoor temperatures and other relevant conditions are assumed to be constant over 24 hours and all free energy gains such as solar radiation are fully utilised. Therefore such programmes do not respond accurately to buildings with changes in operation, to buildings with high thermal mass or large windows.

A widely used programme of this kind in Sweden today is ENORM (1996). This is a steady state programme that was introduced around 1990, as an inexpensive and simple engineering tool to establish conformity with regulations according to the EP approach. It was adapted to the capacity of common personal computers at that time. According to several validations on multi-dwelling buildings, for instance by Adalberth (2000, paper 3, p 18) and Sandberg (1998) the actual energy use was underestimated. This type of steady state computation can be used with reasonable accurateness for simple one-family building or, after thorough calibration, on more complicated structures such as multi-dwelling buildings. It was therefore deemed unfit as a tool to predict energy use for different alternatives in general multi-dwelling building cases.

Semi-steady state programmes take the dynamic effects of free gains, indoor temperature variations and thermal storage into account, in a simplified way. A so-called utilization factor is defined based on a function of the heat loss, heat gains and the time constant, of the specific building. The time constant is defined in Section 4.6.1. Semi-steady state programmes also permit estimations of cooling requirements to limit excessive temperatures during summer.

The European and ISO standard energy performance of buildings – standard, prEN ISO 13790 (CEN 2003), employs the semi steady-state approach, but envisages dynamic programmes as an alternative.

Johannesson (2004) has developed a semi steady state programme based on the European standard. This programme has been developed for two private companies, and is not available on the market. On version, the 'Consolis tool', has been put to the disposal of research projects by one of the companies, and the programme developer. In Annex 5.C the summary sheet of the Consolis tool is presented. Note that it is possible to calculate two different alternatives in the same programme run. This programme includes calculation of heat bridges, which can influence the energy performance substantially if connections between components are not properly designed. The Consolis tool furthermore contains an extensive set of climate data. As the programme is spreadsheet based it is easy to communicate input and output data with other routines within the toolbox.

Dynamic programmes give the opportunity to model the energy use, effect requirements and indoor temperatures according to realistic thermodynamic models. The heat balance for shorter time steps, normally one hour, is computed. With the computing capacity of current personal computers this is no problem, and there are several user-friendly dynamic programmes available in Sweden see, Bergsten (2001). As energy is a critical aspect both with regard to economy and environment, it was deemed appropriate to equip the ILCD toolkit developed in this work with a dynamic programme to obtain accurate prediction of the energy performance of different design alternatives.

The commercially available VIP+ (2000) is a dynamic programme that 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 according to Johannesson (1981). The programme has no specific routine to calculate heat-bridges, which instead can be modelled as any other element of the building. This is a bit cumbersome but gives good understanding of the impact of the heat-bridges. One useful feature of VIP+ is that also indoor temperatures are computed, which allows an assessment of thermal comfort for the specific design alternatives. It should be pointed out that VIP+ primarily is an energy balance programme for the design of the climate shell, and that in general cases, other types of programmes should be used for the thermal comfort related design in general cases. For a normal Swedish residential building with limited window areas, no air conditioning and moderate internal gains, VIP+ is however deemed to be a sufficient tool to predict indoor temperatures. One problem with dynamic programmes is that the hourly time step requires very comprehensive climate data, which are expensive to obtain from the meteorological institutes. In Annex 5.B the summary sheet of a VIP+ calculation is displayed. Further results, such as indoor temperatures or cooling effects, can be obtained from the calculations as text files, which can be copied into spreadsheets. These results are delivered on an hourly basis so that the thermal conditions in the building can be predicted in great detail.

For general applications, such as multi-family dwelling buildings, dynamic or semi-steady steady state programmes are necessary to obtain reasonable accuracy. The calculation tools selected for the toolbox are the VIP+ and the Consolis tool. Thus the following aspects, which are deemed important for a holistic energy design of a residential building, were covered: Energy losses and gains including heat bridges, indoor temperatures, and effect requirements on heating system.

5.6.2 Verification of energy balance calculations

The VIP+ programme and input data were verified by an examining the actual energy use with computations for two different years, for a project that was relatively simple to model. The building cf. Figure 5.2, has simple geometry, no basement and there is no external shading of the solar radiation. The project is further described in Section 4.11.2.

Figure 5.2 Erlandsdal, Svedala. Project used for verification of energy balance programme. Photos by the author.

Charged energy use for space heating and domestic (in the households) and common electricity, during 2000 and 2001 was obtained from the owner of the building. In order to refine the evaluation of the programme, 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 during the heating season; 22ºC, and the number of tenants; 16, were determined by the questionnaire used for the survey on the indoor climate described in Section 5.7.

Climate data for the city Lund, situated 20 km from Svedala, for the two years 2000 and 2001, were 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 for the two years, 2000 and 2001, was used. This energy use was higher than the average energy used for hot water in Swedish residential buildings. That can be explained by the fact that each flat was equipped with washing facilities, instead of one common laundry room for the whole block. Furthermore the size of flats is smaller than average, why the hot water consumption per square meter is higher than the average, cf. Table 4.10.

The common electricity at Erlandsdal did not contribute to the energy balance of the building, since there is, in principle, no such electricity consumed within the climate shell. The household electricity used during 2000 was obtained from the supplier, and was 13914 kWh, which corresponds to 3,05 W/m^2 and is regarded as a free gain.

Heat gains from people were calculated by estimating a release of 80 W/person, and assuming that the tenants where at home half the day. This corresponds to 1,23 W/m^2. These free gains: 3,05 + 1,23 = 4,3 W/m^2, are reasonably in line with the value 5 W/m^2, assumed in the EN-ISO calculation standard, described in Section 4.6.

The calculated results for each year are shown in Table 5.1. The measured energy was 144,5 kWh/m^2, which is 8% more than the calculated 133,7 kWh/m^2, in year 2000, and 150,5 compared to calculated 145,6 kWh/m^2, or 4% more in year 2001. These results can be regarded as satisfying. The calculation errors are related to tenant behaviour and to technical aspects, such as:

- The efficiency factor 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 climate shell, 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 5.1 Case study: Calculated energy balance (kWh/m²). (Öberg, 2002)

	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 calculation.*
*** Theoretical cooling required to maintain a maximum temperature +28ºC. This is used in the calculations since window ventilation is presumed, when this temperature is reached.*

To examine the reliability of the calculations in more detail, Diagram 5.4 shows the calculated and measured energy for space heating and hot tap water month by month. The calculations and measured values agrees well, except for March and April 2000, which is probably due to mixed up readings of charged energy.

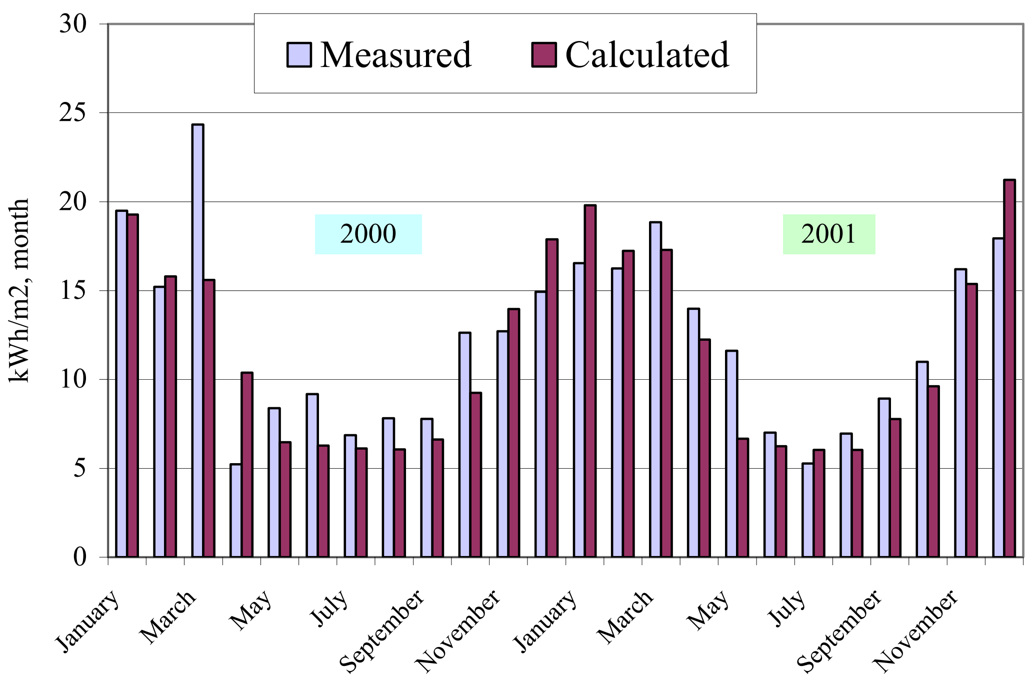


Diagram 5.4 Calculated and measured energy use for space heating and hot water in Erlandsdal 2000 and 2001. (Öberg, 2001)

5.6.3 Energy balance and effect calculations in the ILCD toolbox

VIP+ is used as the base to compute energy use. The Consolis tool is applied to assess the effect of thermal bridges in the pre-design phase, and in some cases also as a rapid alternative to VIP+. The programmes have been run on the same building and climate with good agreement, cf. Annex 5.H.

A spreadsheet-based routine to determine the effect requirements for heating, for different design alternatives, according to the Swedish standard SS 024310, has been developed, cf. Annex 7.A, Table 7.C.4. This is based on the time constant, which is computed as the heat capacity of the building divided by the losses by transmission, air leaks and ventilation, cf. Section 4.6.1. Design temperatures for different locations in Sweden are given in the standard. The energy losses are obtained from the energy balance calculation and the heat capacity is calculated as the sum of weight of components inside the climate shell, times their specific heat.

5.7 Durability

Service life design of concrete follows the report by the Swedish concrete association (SBF, 2002), and the European concrete standard EN 206-1 (CEN, 2000) with its national Swedish application documents. For determination of concrete covers a Swedish standard, SS 137010 *Concrete structures – Concrete cover* was applied. For structures exposed to more severe environment deterministic methods can be applied. Examples of both methods of are given in Chapter 6.

Service life design of components and systems, other than concrete, is experienced based. The periodic maintenance guide by SABO (2001) contains data on technical service life and periodic maintenance intervals. This is included in the ILCD toolbox.

5.8 Robustness

The combination of a qualitative assessment, proven technical solutions, and quantitative predictions presented in Section 4.8, is applied. The following generic list of items for qualitative-quantitative design is proposed for the specific application, Swedish multi-dwelling buildings:

- Roof, with regard to rainwater and condensation.
- Exterior walls including connections to windows, interior floors and base with regard to air tightness, moisture conditions, heat bridges and rain water exposure.
- Slab on ground with regard to ground moisture.
- Ventilation system, including air intakes, with regard to thermal comfort during the heating season and thermal comfort during summer.
- Local weather conditions. (Wind, driving rain, moisture)
- Other specific ambient conditions such as risk for vandalism.

It is proposed that these six strategic aspects complemented by project specific items are examined specifically in the early project phase. They should furthermore be controlled through the design and construction phase, and finally be included in the feed-back routines. An exam

5.9 Lifetime usability – flexibility and service life planning

For lifetime functionality a qualitative method is proposed whereby design options with different possibilities are outlined. Any increase in production cost and environmental burden is mapped and the added value by increased flexibility is taken into account by the MADA, cf. example in Section 5.14.

Referring to the research question defined in Section 3.3.6, a modular service plan was elaborated based on the application example in Section 7.8 representing a typical medium sized rental multi-dwelling building. A service interval of n x 15 years, with n = 1,2,3,4 was found suitable. The following principal packages were identified for that case and are deemed to be representative for modern Swedish multi-dwelling buildings, after SABO (2001):

i. 15 years: Maintenance of furnishings and surfaces, mostly inside flats and exchange of white goods.
ii. 30 years: Additional exchange of windows and bathroom equipment.
iii. 45 years: Exchange of some heavy equipment such as elevators and roofing material (concrete or brick tiles or sheet steel)
iv. 60 years: Major repairs and exchange of installations. Changes with regard to configuration of flats or use of the building.

Given those sequences the tentative modular lifetime plan according to Figure 5.3 is defined. This plan is the base for service life design of the building. In Section 7.8 a detailed example on maintenance plan is given.

	Activity	Year	15	30	45	60	75	90	105	120	135	150	165	180
i	Surfaces, white goods		x	x	x	x	x	x	x	x	x	x	x	
ii	Windows, bathroom..			X		X		X		X		X		X
iii	Elevators, installations..				X			X			X			X
iv	Major renovation					X				X				X

*Figure 5.3 Packaging of maintenance activities from 'x' lighter maintenance to '**X**' major renovations and exchanges*

One important item, that must be included in the maintenance plan, is the façade. Depending on the specific material this, however, varies significantly and therefore no generic interval is proposed. Applying the data in SABO (2001), in the sequences defined above, the following maintenance plans are plausible:

- Rendered façades require either a 15-50% renovation every 30 years, or a lighter make up every 15 years and a 100% renovation after 45 years, depending on climatic conditions and type of bearing structure.
- Concrete façades require painting or washing after 15 to 30 years, depending on ambient conditions. The total service life with regard to deterioration can be designed, according to the client's requirements, with reasonable accurateness, cf. section 4.7.
- Sheet steel façades require painting every 15 or 30 years depending on ambient conditions, and exchange after 45 years.
- Wood panel façades require painting every 7-8 years and exchange after 35 years. The service life is possibly be longer in a dry and cold climate and shorter in a mild and wet climate.
- Brick façades require a lighter renovation after 40 years (Persson, 1999).

Figure 5.3 indicates that:

- Selection of total lifetime of building preferably should be 50-60, 120 or 180 years. These are design life alternatives for the supporting structure.
- Major renovations should be undertaken at 45, 60, 90 years. By detailed design it may be possible to coordinate the 45 and 60 years activities. These are design life alternatives for the long life constituents of the 'infill'.
- Each 30 years some renovations and exchanges take place, which establishes the design life for the medium lifespan 'infill' systems.
- Each 15 years primarily surfaces and white goods need to be dealt with. This primarily relates to actions inside the flats.

5.10 Architecture

Referring to the discussion in Section 4.10, no specific ILCD tool was deemed relevant for this attribute.

5.11 Life cycle cost

5.11.1 Contents, organisation and basis for calculation

The LCC spreadsheet tool included in the ILCD toolbox was developed from, and tested on the buildings in the case study, cf. Section 4.11.2. In Annex 5.A, Table A1, the summary page of the LCC spreadsheet is presented. There are two separate tables; annual costs and present value. The data on shaded background is inserted by the user. Sensitivity analysis can easily be performed with regard, for instance to length of calculation horizon, price increases or end of life scenario.

Each cost item is defined on a separate sheet, compare examples in Appendix 5.A Table A2. On these sheets there is information about typical average costs, cf.

Section 4.11.1 that can be used instead of specific figures, at early phases of a project, or at other occasions when detailed information is not available.

The LCC spreadsheet is organised to be in line with practice for facilities management of multi-dwelling buildings in Sweden (MKB, 2003), as given by national statistics (SCB, 2003), and with the Norwegian LCC standard for construction assets, NS 3454 - *Life cycle costs for building and civil engineering work,* cf. Figure 2.10. It is easy to expand or modify the spread sheet to suit any other particular configuration. The cost items are clustered into:

- Capital costs. Initial cost, tax and residual cost at end of life cycle
- Operating and management costs that are treated as being the same every year
- Periodic maintenance. Scheduled maintenance and replacements that occurs with longer intervals than one year.

The discount rate selected for the LCC calculation affects the result as discussed in Section 2.4.2. For this work a discount rate was sought that would be neutral in terms of rating the future in comparison with present occurrences.

The discount rate for the environmental, socio-economic estimations, according to Section 5.12, is separated from the economical. As a default value this is set to 0 indicating that the environmental burdens are as significant in the future as they are today, c.f. Section 2.3.

The price change in comparison with the consumer price index is normally small. One exception is energy and other environmentally related prices, which have radically changed at some times during the last decades, and are likely to do so in the future. The user can arbitrarily select price changes in relation to inflation, individually for each cost item.

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 by the design of a multi-dwelling building, a historical average real interest rate can be applied. According to Diagram 5.5, a real interest rate in the range of 3-4% can be derived for the past 30 years in Sweden. This is deemed to be an acceptable assumption for the long-term perspective, but can be changed by the user.

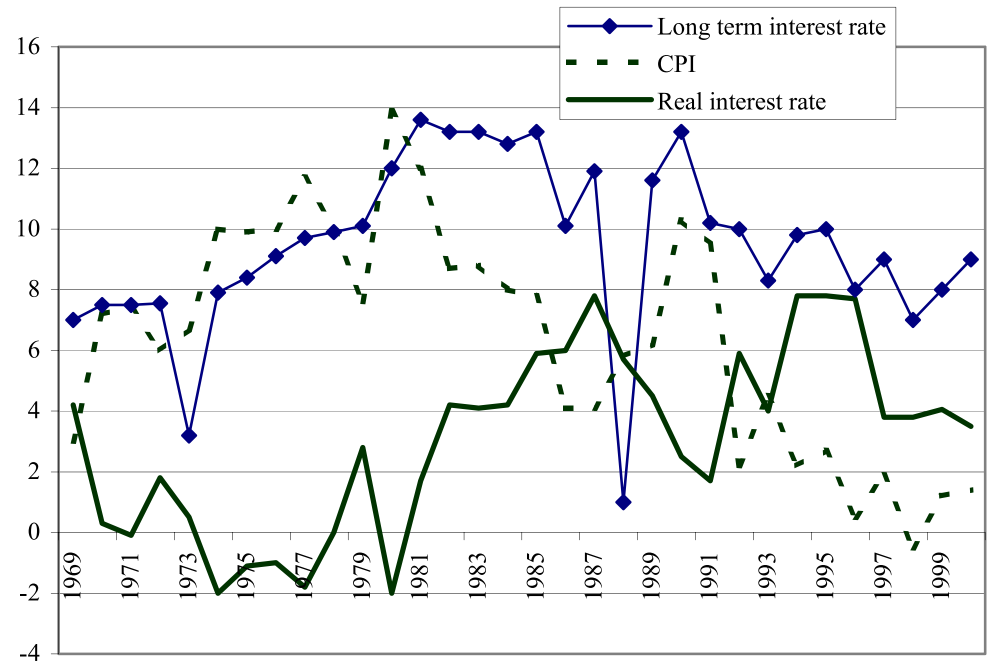


Diagram 5.5 Long-term interest rates on bonds, consumer price index, 'CPI' and real interest rate according to the National Bank of Sweden

The following example shows how the discount rate for a specific future cost is calculated:

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%

The present value of a single future event, or of identical annually recurring future events, are calculated with the standard formulas:

One single future event:

$$PV = P/(1+p)^{t} \qquad (5.5)$$

Identical annually recurring events:

$$PV = P \times (1-(1+p)^{-T})/p \qquad (5.6)$$

Where

P = cost for event at current price level
t = number of years until event occurs
T= calculation horizon (period of analysis in years)
p = discount rate

For the case of periodic maintenance at regular intervals, larger than 1 year

$PV = \Sigma P / (1+p)^{k \times n}$ (5.7)

Where

n = interval in years between periodic activities
k = 1,2,3… as long as k ≤ T/n

To estimate the annualised cost (equal annual costs) over the calculation horizon the following standard formula is used:

$A = S \times p/(1-(1+p)^{-T})$ (5.8)

where

S = The cost at current price level, that is to be distributed

S may represent

- An investment today.
- The PV of annual recurring events according to (5.6). The solution is then trivial, since A then is the inverse to PV.
- The PV of a single or periodic future event according to (5.5) or (5.7).

In the LCC model used in the ILCD toolkit, the user arbitrarily selects the real interest rate and price increase for the specific cost category. The programme calculates the resulting discount rate, cf. Annex 5.A, Table A1. Default values are given according to the discussion above. Sensitivity analyses are easily undertaken, for instance to determine the effect of different price increase scenarios, or with regard to the economical planning criteria applied by the client.

5.11.2 Life cycle cost data

In order to establish an accurate base for life cycle cost prediction, data on building and operating costs were gathered and analysed. Statistical data on costs were collected from several sources and a field-survey comprising four modern concrete multi-dwelling buildings was undertaken. The result of this investigation is presented in Section 4.11 and by Johansson and Öberg (2001).

For periodic maintenance a spreadsheet with relevant information, that is information on maintenance intervals, technical service life and cost for maintenance activity, was developed based on data in SABO (1999), after a format presented by Persson (1999). In Annex 5.A Table A3, the periodic maintenance sheet is displayed.

5.11.3 Calculation horizon

One principal question by life cycle costing outlined in Section 3.2 is how the calculation horizon may affect the result. Two aspects must then be considered:

1. When is a reasonable balance between initial and operating costs achieved, and thus a representative long-term cost profile obtained?
2. Will the calculation horizon effect the relation between the alternatives?

With the Life cycle cost module of the ILCD toolbox, sensitivity analysis can easily be undertaken. Six different calculation horizons from 30 to 180 years were examined for the project example in Chapter 6. Diagram 5.6 shows the life cycle costs for the project when calculated with different time horizons. Project data are given in Chapter 6 and a comparison between three different design alternatives is presented in Table 6.8.

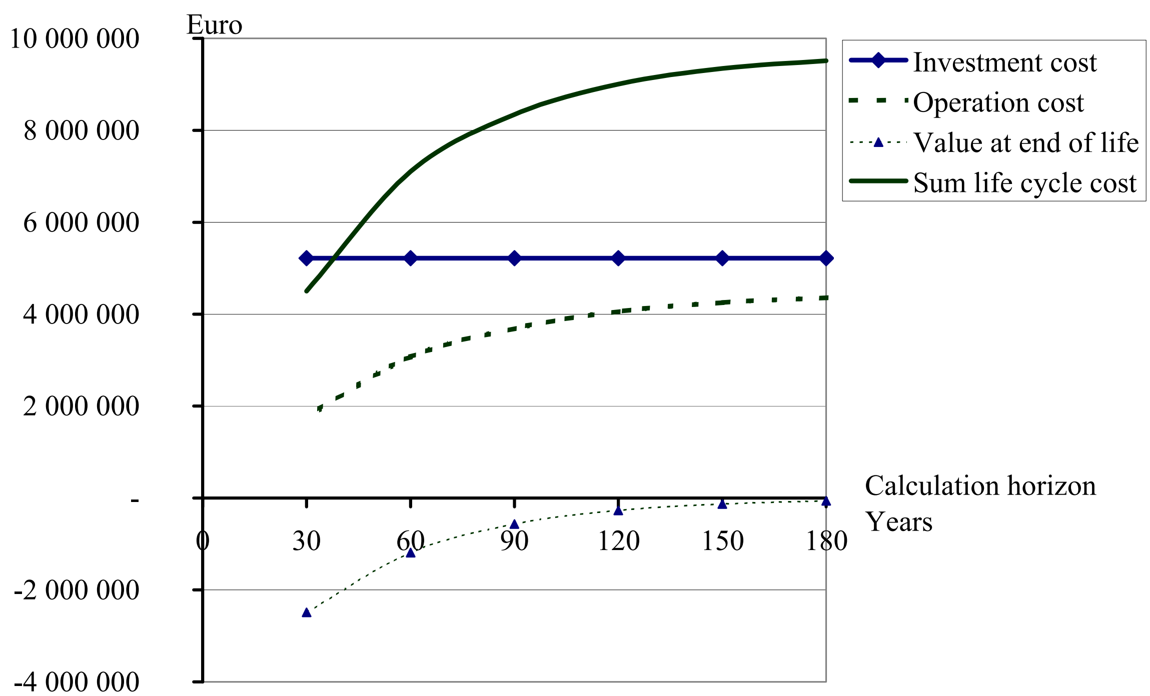


Diagram 5.6 Estimated life cycle cost, expressed as present value, dependent on the calculation horizon. The value at the end of life is displayed as a negative figure in the diagram since costs are represented with positive figures. In this case the real value at end of life cycle is identical with the production cost.

These sensitivity analyses indicate that a minimum of 60, but preferably 100 years, gives a satisfactory balance between investment and operating costs, and furthermore, a relevant ranking of alternatives, as shown by Table 6.8.

5.11.4 End of the life cycle

The end of the life cycle can either release a cost for demolition, and final disposal, or a gain from sales of the building, as discussed in Section 3.2. It may be difficult to predict this at the design phase.

To clarify the impact of the end of life scenario on the total life cycle cost, and thus guide what assumptions should be made by LCC calculations in the design phase, the following sensitivity analysis was undertaken. It is based on the typical Swedish residential building according to the example in Chapter 6.

In the LCC tool there is a specific sheet covering the end of life cycle, cf. Annex 5A, Table A4. Different scenarios can be selected, or a specific cost or residual value, if known.

Also environmental aspects are dealt with here. In case there is a residual value attached to the building the environmental burden of destruction and final disposal is not released. This implies that the end of life scenario here either refers to ownership (second hand value) or building life cycle (final disposal cost and environmental burden), cf. Figure 2.8.

The total annual cost and present value of costs for five different end-of-life scenarios were calculated with the LCC module of the ILCD toolbox, presented above. In order to determine the effect of the calculation horizon three different time spans were also studied. The end of life scenarios tested were:

- 50 % increase of value.
- Identical value.
- 50% decreased value.
- No residual cost or value.
- Demolition and disposal costs 50% of cost of the construction.

Diagram 5.7 and 5.8 summarize the results. The conclusion is that the end of life scenario is important at shorter life spans, such as 50 years, whereas at 100 years this plays a minor role. The difference in present value of total costs between the extreme scenarios, is however still notable at 100 years, cf. Diagram 5.8. This is furthermore a realistic minimum length of life for a Swedish multi-dwelling building. If the end of life scenario is not known, a long (100 years) calculation horizon is preferred in order to reduce the effect of what scenario is selected, on the result.

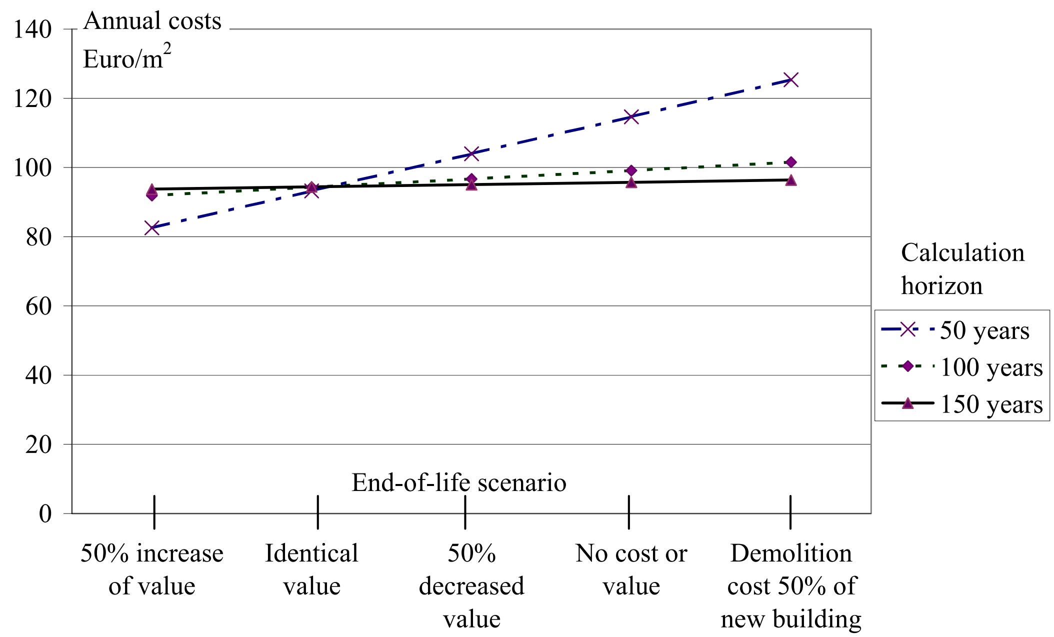


Diagram 5.7 Total annual costs for a typical Swedish multi-dwelling building by different end-of-life scenarios and different calculation horizons.

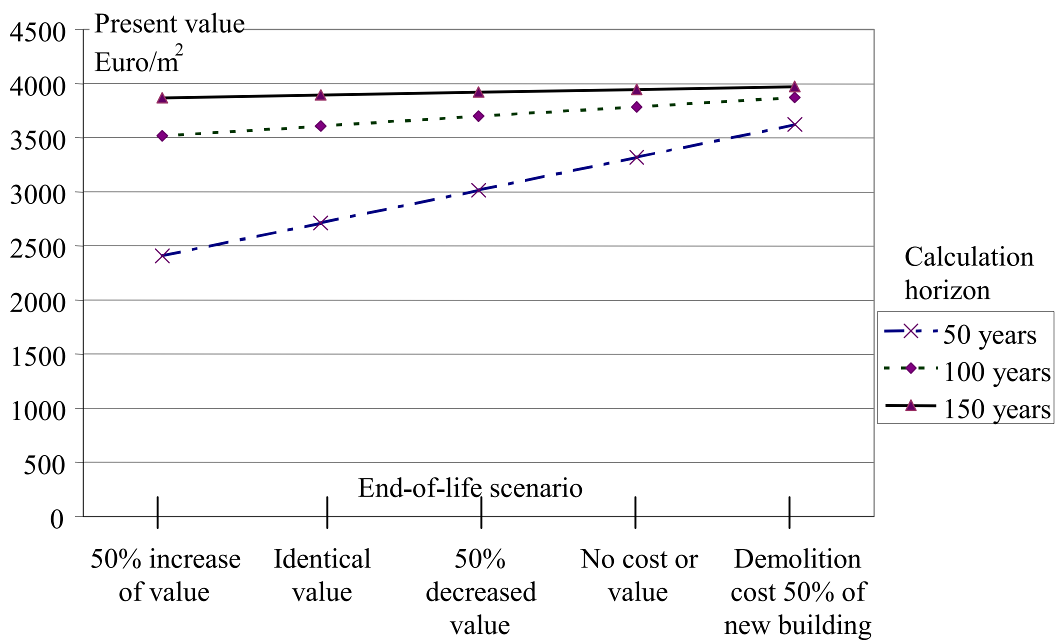


Diagram 5.8 Total present value of cost for a typical Swedish multi-dwelling building by different end-of-life scenarios and different calculation horizons.

5.12 Environmental burden

The energy use for operation has been singled out as the dominant environmental burden emanating from buildings. Therefore energy use has been selected as a simplified environmental life cycle indictor. To open and indicate future possibilities to expand the analysis to full LCA, a supplementary procedure, limited to the concrete structure, is also included in the toolbox. This furthermore provides the possibility to study the environmental consequences by changing for instance floor thickness or concrete quality, for some purpose with regard to functional performance. The toolbox thus includes two alternative environmental assessment methods:

- A simplified method that incorporates the whole building, monitoring the energy use and the related environmental consequences.
- A full LCA model, that in its present configuration only deals with the concrete building frame.

5.12.1 Simplified environmental assessment method

As discussed in Section 4.12.2 energy consumed during the user phase is acknowledged as the most important environmental burden. Energy use by operation is thus utilised as the primary environmental indicator for the ILCD toolbox. Saari (2001) and Sterner (2002), both use this simplification when assessing buildings, even though it is acknowledged that energy use does not cover the entire environmental field. A second reason for this simplification is that complete, robust and reliable quantitative environmental data for building products are only available for a limited number of products and materials, which makes any detailed LCA for a complete building cumbersome and unreliable.

In order to translate energy use to environmental burden a spreadsheet tool was developed that. Given the amount of energy consumed and the particular energy source used, the tool estimates;

i) The resulting emissions to air of CO_2, NO_x and SO_2 of the production and use of the specific energy carrier.

ii) The socio-economic cost of these emissions and energy in terms of air pollution and resource use.

The ‘socio-economy’ is calculated according to EPS 2000 (Steen, 1999), cf. Table 2.3. The unit is a socio economic value as explained in Section 2.5.2.

A database on emissions from different energy sources was developed based on LCAiT (1996) and connected to socio-economic costs according to EPS 2000. The calculation sheets are presented in Annex 5.D.

It is acknowledged that the selection of a limited number of environmental stressors according to item i) above, underestimates the total environmental burden. However, LCA studies on energy and also cement and concrete, such as Vold and Rönning (1995), show that these particular stressors contribute to more than 90% of the total environmental burden, and furthermore that the other stressors occur in good correlation with the ones selected here. Therefore, any environmental comparison between alternatives based on i) above, will be correct. The total environmental burden is thus underestimated with a maximum of 10% in relation to the importance of other attributes. This simplification was done in order to make the model practical to use. If requested it can easily be expanded with any other environmental stressors.

The energy carriers included in the model used in the toolbox are electricity (Swedish average), district heating (Swedish average), natural gas, diesel and oil. Other energy carriers can be added if needed.

5.12.2 Full LCA method

Based on previous work by the author (Öberg, 1997, 1998) and the Nordic LCA project reported on in Section 4.12.4.1, a module for LCA on concrete building frames was developed for the toolbox. The purpose of this was to provide the possibility for more detailed environmental optimisation of the structural frame. This module is based on the generic LCAiT (1996) tool. It can be expanded to include any other type of material or component that is incorporated into the building. Referring to discussion in Section 2.5.4 it was not deemed practicable to compile such general LCA tool for this pilot toolbox due to the current lack of quantitative environmental product data for building materials and components.

The LCAiT tool consists of an inventory procedure where the user graphically defines a process tree; compare Figure 5.4, and description of the LCA procedure in Section 2.5.2 item ii. The tree contains boxes for materials or processes and boxes for transportation of materials. Generic environmental data sets are included in the programme, and the user adds any necessary specific data for materials and processes. The generic datasets include a much more comprehensive list of environmental stressors, than the aspects included in the simplified procedure, according to 5.12.1. In order to obtain compatibility with the simplified method, the valuation in the full LCA method is restricted to the stressors that are included in the simplified procedure. The data applied in the toolkit base LCA version is tabled in Annex 5.F.

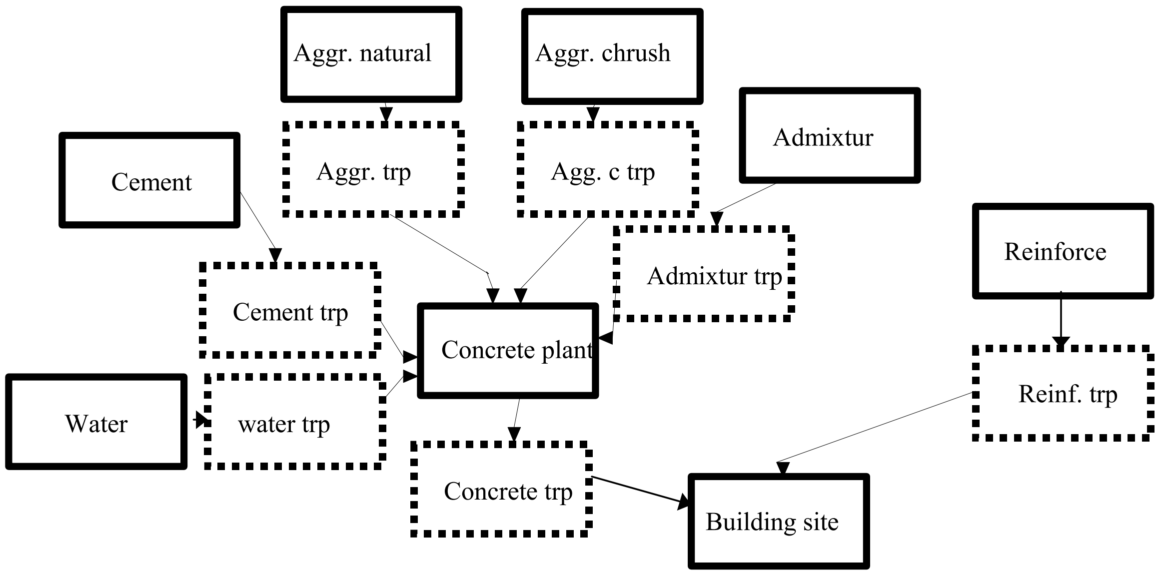


Figure 5.4 LCI process tree for cast in place reinforced concrete, from cradle to finished structure. Boxes with dotted lines refer to transportation while other boxes represent processes or materials.

The programme calculates the environmental stressors occurring as a result from the process from materials flows and energy use. Any kind of environmental stressor can be included in the inventory, provided that the relevant data are stored into the boxes of the process tree. Typically the following stressors are mapped:

- Emissions of different substances to air and water.
- The waste generated.
- Use of energy and resources.

The result is a list of the quantified stressors. This list is exported to a spreadsheet model, developed by the author, that performs the impact assessment, according to the LCA procedure described in Section 2.5.2 item iii, cf. Annex 5.E. As in the simplified energy model according to Section 5.12.1, the EPS weighting method (Steen, 1999) is applied. This also enables comparison between the environmental burden of the building frame and total building life cycle.

To facilitate application of LCAiT to reinforced concrete structures in the toolbox a set of different routines were developed or updated from previous models:

- A generic process tree for reinforced concrete.
- Datasets covering relevant specific environmental data.
- A spreadsheet model to simplify input and output from the programme, including the weighting procedure applying EPS 2000.

5.13 ILCD – criteria

Table 5.2 shows the analysis scheme developed from the ILCD criteria presented in Chapter 4. The scheme can either be used directly by picking one of the categories, or which is deemed more relevant, each attribute can be considered separately, and the category chosen specifically for each category, or given any arbitrary target.

Table 5.2 ILCD Criteria Matrix

Attribute		Lifetime quality category		
		Best practice	Good	Norm
Mec. resistance, stability	1	S1	S1	S2
Safety in case of fire	2	REI 240	REI 120	REI 60
Indoor environment	3	ICC A	ICC B	ICC C
Safety in use	4	Sk3	Sk2	Sk1
Acoustics	5	A	B	C
Energy use	6	65 kWh/m^2	90 kWh/m^2	120 kWh/m^2
Durability	7	180/60 years	120/30 years	60/30 years
Robustness and risks	8	1	2	3
Life time usability	9	50%	25%	No requirem.
Architectural	10	-	-	-
Life cycle costs	11	LCC 4000	LCC 4000	LCC 4000
		Or to be quantified		
Global environment and resource use	12	E.sustainable	E.sound	Acceptable
		Or to be quantified		

1 Stiffnes class. See Section 4.1
2 Refers to < 5 storeys. For 5-8 storeys R=60 in floors and R=90 in vertical structures. For > 8 storeys all R=90. Also compare Section 4.2.
3 Refers to classes defined in Section 4.3.
4 Protection class referring to house breaking, See Section 4.4
5 Sound class according to Section 4.5
6 Energy for space heating, hot tap water and common electricity. Household electricity not included.
7 Target life for support and infill respectively. See Table 3.3 and Section 4.7
8 Insurance class. See Section 4.8
9 Flexibility classification according to Saari and Heikkilä (2003). See Section 4.9
10 Exempt from ILCD criteria, cf. Section 4.10
11 LCC Class [Euro/m^2,100 years]. Or to be quantified for each alternative
12 Environmental classification according to Erlandsson and Carlsson (2004), Or to be quantified for each alternative socio-economic cost according to Section 5.4.1.

Note that if one lifetime quality level is selected consequently, throughout all attributes there may be contradictions built into the specification. For instance low energy consumption and good global environmental performance may, but does not have to, be in opposition to best available indoor environment. The challenge in the specific project is to find technical solutions that can fulfil both requirements, or to obtain the optimum compromise from the client's point of view. In order to highlight this very important aspect, identical life cycle costs have been proposed as default values for the three quality categories. This implies that a high quality building need not be more expensive than a lower quality building in the life cycle perspective. The author acknowledges that this is only a hypothesis. However, results from this research work does not contradict that statement, see for instance Chapter 6. This is why identical costs have been suggested in the criteria matrix, for the three quality levels. Note that the alternative approach to fix the functional criteria and calculate the resulting life cycle cost can also be applied.

When comparing performance it is important to take any redundancy with regard to criteria into account. This is discussed in Section 3.3.2.

Performance objectives should preferably be expressed in standardised performance classes, and, when possible, as functional rather than prescriptive criteria. Functional criteria have the advantages compared to prescriptive that they:

- Respond directly to the specific attribute.
- Are more representative of the real integrated performance. For instance the effective energy performance of a building depends on the characteristics of the individual components and systems, such as U-values and air exchange rates, but also on the compatibility between structure, heating and ventilation systems, and their operating regimes.
- Open possibilities for alternative design solutions.

5.14 Multiple attribute ranking aid according to ASTM (1998)

MADA (cf. Section 2.6.2) 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 the performance of selected aspects. This section presents an example of the application of principles for multiple criteria decision-making in buildings. It also presents the simplified MADA routine that was developed for the ILCD toolkit based on a spreadsheet tool.

5.14.1 MADA application 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 was chosen because it is deemed representative for an ordinary design situation.

5.14.2 Hierarchical decision tree structure and decision matrix.

According to MADA principles, a hierarchy for the selection problem is drawn up. This is defined as the decision tree, cf. Figure 5.5. More than two levels of attributes may be used but according to ASTM ten levels is the practical limit. The attributes that are placed at the end of a branch are defined as leaf-attributes.

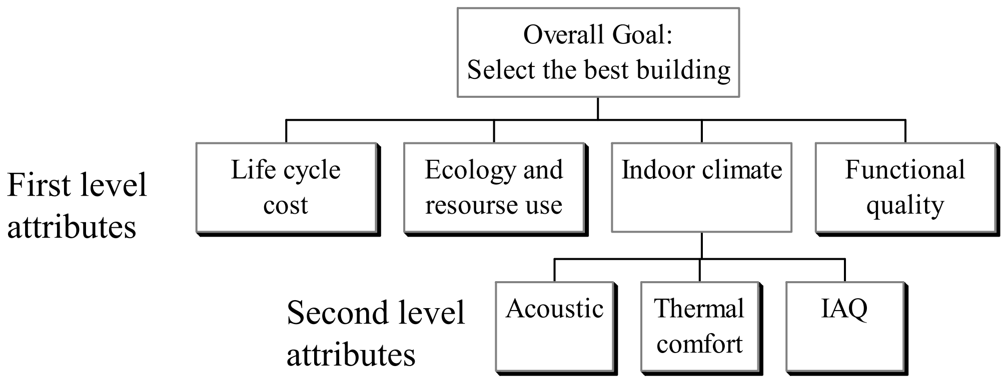


Figure 5.5 MADA Decision tree. End or' leaf attributes' with thick edge lines.

The next step is to compile a decision matrix covering all attributes, see Table 5.3.

Table 5.3 Decision matrix

Attribute		Performance of alternative			
Level 1	Level 2	**α**	**β**	**γ**	Unit
Life cycle cost. 50 years		1765	1780	1770	Euro/m²
Environment. burden		340	335	345	ELU/m² (Soc.ec)
Indoor climate	Acoustics	B	B	C	Sound Class
	Thermal comfort (indoor temp.)	36	12	60	Days/ year >28ºC
	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.*

The example is a simplification, where only one group of sub-attributes is considered. Three different construction alternatives are compared: **α, β** and **γ**. Life cycle costs and environmental burden have been calculated for the alternatives and are compiled in Table 5.3, together with the assessed functional quality for the other attributes, for each alternative design.

The example presents in detail how parameters measured by numerical units, classes and verbal expressions are integrated in the analysis. Values that are expressed in figures can be used directly, but verbal expressions and classes need to be digitalized.

For a simplified analysis it is possible to stop at this point. The tree and the matrix give a good overview of the decision situation. Evaluation of environment and economy can be integrated by the socio-economic approach, where the environmental burden simply can be added as a monetary cost.

5.14.3 Paired comparisons

The decision matrix is processed with paired comparisons between

- The alternatives for each leaf attribute.
- The attributes for each attribute level.

Table 5.4 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, can thus be dealt with using matrices of paired comparisons. Table 5.4 presents a matrix of paired comparisons. Note that values on opposite sides of the diagonal are inverted. Tables 5.5 and 5.6 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 5.5 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 5.6 Digitalisation and pairwise 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 paired 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 5.6, 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 Annex 5.G:

Life cycle cost for alternatives **α,β,γ** according to Table 5.3: 1765; 1780; 1770.
The first row of the matrix of comparison gives: 1; 1765/1780; 1765/1770 i.e. 1; 0.99; 0.99. Since higher costs render quotients less than 0, these should not be inverted.

Life cycle environmental burden for alternatives **α,β,γ** according to Table 5.3: 340; 335; 345. The first row of the matrix of comparison gives: 1; 340/335; 340/345: i.e. 1; 1,01; 0,99. Since higher energy use renders quotients less than 0 these should not be inverted.

Acoustics for alternatives **α,β,γ** according to Table 5.3 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 5.3: 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 5.3; 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 5.3: 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 indoor air quality. 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 5.4.

Aggregated values for all attributes, and the final ranking between alternatives, are shown in Table 5.7. 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 Annex 5.G.

Table 5.7 Final ranking of alternatives in the example

	Alternative **α**	Alternative **β**	Alternative **γ**
LCC	0,40	0,397	0,400
Environmental burden	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**

5.14.4 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 5.6, 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 5.8. This will affect the result of the calculation. The crucial factor is the desirability for row 1 over column n, compare Table 5.7.

Table 5.8 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

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 5.3, 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).

It is very important to be aware of the sensitivity of the digitalisation. MADA can also be performed in a simplified way where the hierarchical tree structure is used to systemise the options, and the decision matrix is used to clarify and present the quality of the different alternatives. Then a combined qualitative and quantitative ranking of alternatives is facilitated.

A generic MADA process tree and decision matrix could be developed based on the ILCD criteria presented in Table 5.2. It is however deemed more adequate to compile specific MADA sets for the individual client or project in order to obtain a practicable system. The number of possible sub attributes is large, and even if a very complex and large generic decision matrix is established, it is likely that there will be items missing for the specific application. Furthermore the method will then become onerous to operate. Examples on MADA applications are given in Chapters 6 and 7. One MADA model has been developed and included in the ILCD toolbox for direct use or re-configuration to suit any other set of criteria.

5.15 Feed back

Systematic recording, and feedback of information, of the performance of the chosen technical solutions facilitates continuous improvement, and makes it possible to avoid repeating mistakes.

5.15.1 Production phase

Follow up from the production phase covers traditional productivity aspects such as costs and production times. For Swedish cast in place concrete buildings there is a reference database available by SFF (2000), presenting a large number of projects including costs and production times, as well as material data. For improved constructability of technical solutions it is also important to monitor specific and strategic points, such as connections between construction elements, both with regard to simplicity by execution and achieved technical quality. Methods such as thermography can be applied to check for air leaks, which may be caused by poor design detailing or execution. This method was tested by the examination of the Erlandsdal project, cf. Section 5.6.2. The results and experience was presented by Burke et al (2002).

5.15.2 User phase

Of the criteria stated in Table 5.2, indoor environment including acoustics, energy use, moisture conditions and life cycle costs are relevant to measure and compare with the design objectives. In some cases also mechanical properties such as deflections, cracking and vibrations may be valuable to assess.

Life cycle cost can be followed up relating to the maintenance plan, cf. Section 5.9 and example in Section 7.8.

Charged energy use is automatically measured, and can be compared with calculation results after correction for the specific climate.

The indoor climate is a more complex aspect that cannot be fully assessed quantitatively. To design for a comfortable and healthy indoor climate is a multi-disciplinary task that needs consideration both regarding the building structure, its service systems and their interaction. In the method by Carlsson et al (2004), referred to for comfort criteria in Section 4.3, verification methods are also presented. These are standardised methods to assess the quantitative criteria, for instance, insulation for air borne sound or CO_2 content in air.

The quantitative methods are complemented with a qualitative method based on a Swedish standard questionnaire on perceived indoor climate, that have been used extensively since the early 1990s: 'Stockholms innemiljöenkät' (Engvall and Norrby, 1992), which is a questionnaire aimed at general evaluation of indoor climate. This is equivalent with the PPD-index described in Section 4.3.5. The result of the questionnaire is presented in the form of profiles of complaints covering; indoor temperature, ventilation, acoustics, light and health. The result can be compared with a reference, based on a survey of over 10000 households in Stockholm, distributed by age of building, type of ventilation system etc. This reference is one primary feature of the questionnaire, which enables a direct benchmark with a large reference. The questions are answered with a five step scale. In some areas such as by assessment of thermal comfort and acoustics, seven step scales are often preferred by research. When comparing results expressed in terms of % satisfied this must be observed.

The questionnaire by Engvall and Norrby was deemed to be the most adequate tool for qualitative feed back on indoor climate, and was thus selected for the ILCD tool kit. The survey was tested on the entire set of nine, identical buildings with a total of 64 flats in the Erlandsdal project in Svedala, cf. Figure 5.2. This is the same project that was used for the verification of the energy balance programme included in the ILCD tool. Apart from the purpose to study the indoor environmental performance of a normal modern concrete multi-dwelling, the survey was done to examine the applicability of the method.

After sending out two reminders, an answering rate of 88% was achieved, well in line with the requirement of 75% to achieve reliability of the survey. The resulting complaint profile for indoor climate is displayed in Diagram 5.9 for comfort, and in Diagram 5.10 health. In Diagram 5.9 two different references were used: 'A' with the same type of ventilation system as the specific project, mechanical exhaust ventilation, and 'B' with supply and exhaust ventilation, referring to the base study mentioned above.

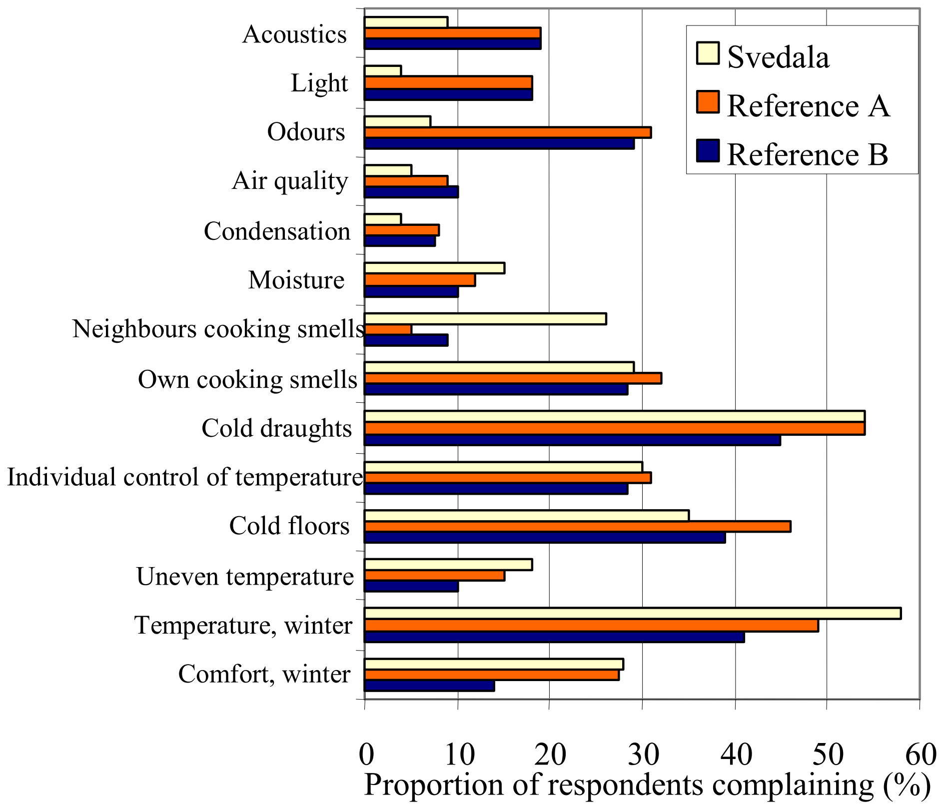


Diagram 5.9 Indoor climate (comfort) complaint profile for Erlandsdal, Svedala.
Reference A refers to mechanical exhaust and B to supply and exhaust ventilation.

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.

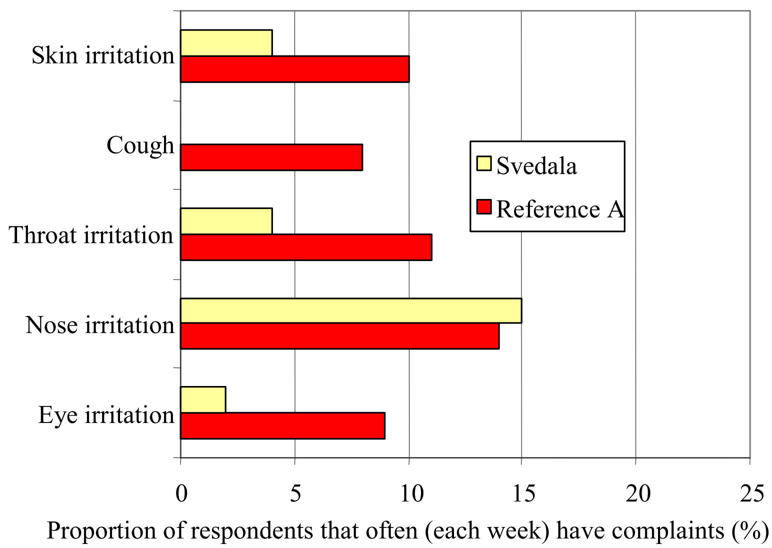


Diagram 5.10 Indoor climate (health) complaint profile Erlandsdal, Svedala

Further to the 45 specific questions in the questionnaire, the respondents were invited to include any other comments. A recurring remark relates to 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, reference A, and also in the Svedala project, is a weak spot. Cold air from the intakes, above the windows, leads to dissatisfaction with the thermal comfort during the winter. Particularly during milder periods when the radiators below the windows are not hot enough to counter the cold fresh air. To counter the cold draught, the tenants, in several cases, had blocked the air intakes. Blocked air intakes may result in opposite air streams through the ventilation system, which in its turn explains why the smells from the neighbours cooking may spread. This was also given a high complaint rating here.

Mechanical exhaust ventilation systems in general, reference A, behave less satisfactorily than supply and exhaust ventilation systems, reference B, when it comes to thermal aspects, compare Diagram 5.9 and Annex 4.A, Diagram 4.A.2.

The method was easy to apply and the results gave valuable information on the performance of the building and its service system, which confirms the importance of systematic feed back of information.

5.16 Conclusion on the ILCD toolbox

A generic set of criteria relating to the analysis of fundamental attributes on residential buildings in Chapter 4, has been developed, cf. Table 5.2. Criteria should, if possible, be connected to standardised methods for verification. Then systematic follow up of the result of a specific design is facilitated, both with regard to actual performance, and were relevant, also constructability.

A toolbox for simplified ILCD has been developed featuring the following main functions:

- Tools for prediction of energy use and acoustic properties.
- Quantitative data on long-term performance of components and materials.
- Life cycle appraisal methods covering economy and environmental burden.
- Methods to aid decision-making and optimisation.
- Principles and methods for feed-back.

Some of the tools are publicly available programmes while other tools were developed in this work. The toolbox is open and available for use by design, or for further development.

Environmental book keeping is linked to economy by socio-economic assessment of the environmental burden. The relationship should be regarded only as indicative. The following aspects need further clarification:

- General agreement on the valuation of different environmental impacts.
- The risk that environmental burden, or a part thereof, is accounted for twice as the cost of, for instance on energy or waste treatment may include an environmental tax.
- The range of environmental stressor taken into account in this work is restricted, implying that the environmental burden is underestimated.

The direct applicability of ILCD by design is a core objective of this work. Simplicity in use, adaptability and transparency are therefore prioritised. The toolbox can be applied with increasing level of detail following the design process from early sketches to tender and construction documentation.

6 THEORETICAL BUILDING – DESKTOP STUDY

This chapter presents a theoretical design task where the ILCD toolbox, cf. Chapter 5, is applied to define design criteria, specify technical solutions and assess the lifetime consequences of three different alternatives.

6.1 Background

Application of the pilot toolbox to real projects, as presented in Chapter 7, many of which are in a late phase of planning, implies that the task and choice of alternatives are restricted. In order to examine and present the full possibilities of the ILCD toolbox, when applied from the start of a project without any specific limitations, a theoretical building was modelled.

An additional aim of this desktop study was to map the consequences with regard to life cycle cost and environmental burden, by selecting the minimum, or the best available functional performance quality.

6.2 Task

The task of this study was to:

- Examine the possibilities and shortcomings of the ILCD methodology and in particular the toolbox that has been developed.
- Map the life cycle cost consequences induced by changes in functional quality ranging from best practice, 'BEST' to minimum norm standard 'NORM' with a third intermediate alternative 'GOOD'.
- Map and analyse environmental consequences related to the production of the different alternatives with regard to structural frame.
- Examine how the toolbox can be applied also for a limited task such as evaluation of a specific system or component. A study on balconies with regard to service life and durability was undertaken to this end.

6.3 Method

A theoretical multi-family dwelling building was outlined in three different functional quality levels. The consequences with regard to technical solutions, life cycle economy and environmental burden were mapped according to the following steps, cf. Section 3.3. Reference is given to boxes marked I to III, in Figure 3.3.

- Definition of performance requirements for the three quality levels. (I)
- Definition of technical requirements for the different quality levels. (I)
- Design and present the technical solutions relating to the quality levels. (I)
- Estimate the life cycle cost consequences related to the quality levels. (II)
- Estimate the environmental consequences related to the quality levels. (II)
- Rank the three alternatives according to the ILCD model. (III).

A specific geometrical layout for the project, and the number of flats, were defined as boundary conditions. See Figure 6.1. The outline is a typical Swedish point-block, with average sizes of flats, similar to Example A, in Chapter 7. Also compare sketches in Annex 6.A. The author selected the following materials and systems:

- Façade: Brick clad with mineral wool insulation. Gables of load bearing concrete. Long sides of a curtain wall with steel studs.
- Interior walls separating flats: Concrete.
- Interior floors: Concrete with parquet covering and ceramic tiles in wet rooms.
- Roof: Ventilated with insulation on concrete slab, covered by concrete tiles on timber framework.
- Ventilation system: Supply and exhaust ventilation with heat recovery on exhaust air, or mechanical exhaust ventilation.

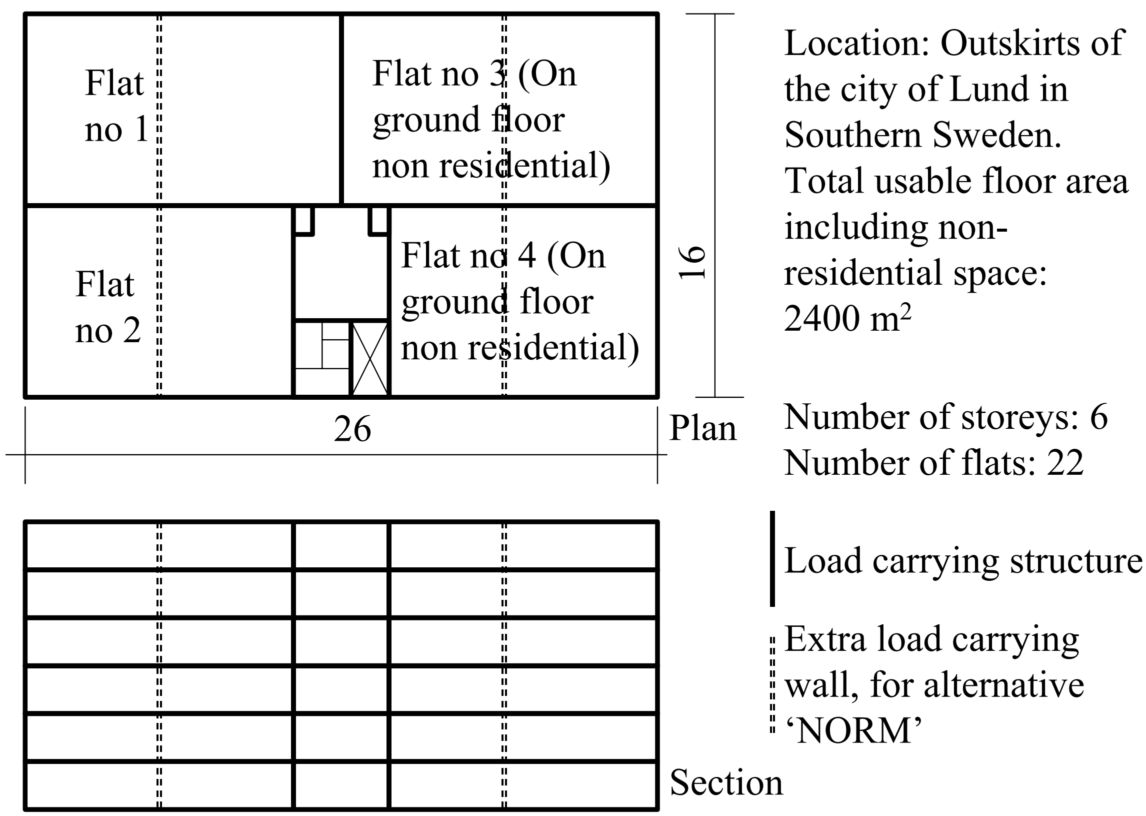


Figure 6.1 Geometrical outline and general data for the desk top study.

The following aspects varied between the alternatives:
- Thickness and concrete grades of concrete slabs and walls.
- Ventilation (type and air exchange rates).
- Thermal insulation of external walls, roof and windows.
- Net floor area due to required space for ventilation and thickness of walls.
- Extra load carrying wall due to smaller spans for alternative.

6.4 Performance requirements

This section describes the first step in the ILDC model presented in Figure 5.1, comprising analysis of the client needs, and on the pre-design phase where these needs are transformed to an initial programme for, and outline of, the building.

The different designs were selected according to the three different lifetime quality levels, of the criteria matrix in Table 5.2. These represent a range from best current practice, to minimum standards according to norms. Note that in practice, different quality levels can be attached to the various attributes for one design alternative. It is thus not necessary to follow one quality level consequently, as it is done in this example. The alternatives were coded: 'BEST' (Best practice), 'GOOD' and 'NORM'. With regard to energy performance also a 'best available technology' alternative was examined.

Table 6.1 Functional quality requirements on the alternatives

	Quality level		
Attribute	**BEST**	**GOOD**	**NORM**
Mechanical resistance, stability	S1	S2	S3
Safety in case of fire	REI 120	REI 120	R 90/EI 60
Indoor environment	ICC A	ICC B	ICC C
Safety in use	PL 2	PL 1	PL 1
Acoustics	A	B	C
Energy use	70 kWh/m^2	90 kWh/m^2	120 kWh/m^2
Durability. *Support/Infill	180/60 years	120/30 years	60/30 years
Robustness and risks	1	2	2
Life time usability	Change of size of flats	Flexible interior walls	No requirement

Classifications are explained in Table 5.2
** Service life, cf. Section 3.3.6.*

6.5 From performance requirements to technical specification

The methods applied to address the functional performance criteria refer consequently to the ILCD toolbox presented in Chapter 5. In this section each attribute is discussed. The design tools and the resulting specification are presented.

6.5.1 Structural design

A pre-design tool for cast in place concrete was applied (SFF, 2000). The structural principle according to Figure 6.1, with and without alternative extra load carrying interior walls, was studied. Façades are considered load bearing with no fixed ends. Thus either a concrete wall, or steel columns incorporated in a curtain wall, can be selected as load carrier in the façades. The structural alternatives for concrete slabs according to Table 6.2 are available.

Table 6.2 Alternative structural designs of concrete slabs according to SFF (2000)

	Large free spans*			With extra wall*
Concrete grade[12]	C25/30	C35/45	C50/60	C25/30
Minimum height of slab (mm)	325	270	230	180
Reinforcement. (Kg/m^2)	5,6	5,9	6,4	4,1

** Cf. Figure 6.1 and Annex 6.B, Figure 6.B.1*

6.5.2 Fire safety design

The handbook pre-design method is applied. According to BE (2001) the structural dimensions according to Table 6.3 are required:

Table 6.3 Fire safety pre-design of structural frame. (minimum dimensions)

Alternative	Fire class	Structure	
		Wall between flats	Floor
BEST, GOOD	REI 120	120 mm	160 mm with 32 mm concrete cover by 100% utilization of reinforcement
NORM	R 90 / EI 60	100 mm	100 mm with 25 mm concrete cover by 100% utilization of reinforcement

6.5.3 Indoor climate design

As concluded in Section 4.3, it is the comfort related requirements that are relevant when comparing alternatives, as the health aspects are threshold limits which always have to be fulfilled. Furthermore the alternatives are assumed to be identical with regard to, for instance, self-emissions from building materials. However, there is one indirect health related consequence related to the alternatives. The thickness of the concrete slabs and concrete composition requires different drying times, in order to reach the necessary relative humidity to avoid risk of reaction with any bonded flooring system. This affects the production cost of the structural frame. The TorkaS 2.0 (2002) computer programme is used to predict this, and the results are presented in Table 6.4. Two climate cases are studied: Casting in December or in June. In both cases tight building with controlled drying climate is presumed three weeks after casting. The relative

[12] Concrete grade expressed in characteristic cylinder/cubic strength according to European concrete standard EN 206-1.

humidity 90%, in the concrete, was used as target value. The results indicate that GOOD and NORM have similar drying properties while BEST requires approximately 3 more weeks.

Table 6.4 Technical specifications and data of the three quality alternatives

Aspect	Quality level		
	BEST	**GOOD**	**NORM**
Floor thickness (structural), mm	280	240	180
Concrete grade structural floors, cf. Table 6.7	C32/40	C40/50	C25/30
Applicable water to cement ratio for concrete	0,55	0,50	0,65
Drying to RH = 90%, casting December (weeks)	17	14	13
Drying to RH = 90%, casting June (weeks)	14	11	12

The design for indoor climate comfort is based on the criteria given in Section 4.3, which have been compiled in Table 6.5. Thermal comfort is addressed by calculating the theoretical need for cooling to maintain a specified maximum indoor temperature, with the VIP+ energy balance programme. The fresh airflow is controlled by the ventilation rates. This is reflected in the larger energy requirements for ventilation for the GOOD and BEST alternatives, as shown in Table 6.6. The other criteria listed in Table 6.5, such as CO2 concentration or relative humidity, can only be quantified, by measurements of the finished building.

Table 6.5 Criteria for indoor air quality after Carlsson et al (2004)

Aspect/Indoor climate class		Unit	ICC A	ICC B	ICC C
Operative temperature	Winter	°C	20-24		> 18
	Summer		20-26		> 18
Floor temperature	Minimum	°C	19		16
	Maximum		27		27
Air velocity, maximum		m/s	0,15		
Fresh air flow		L/s, m^2 floor area*	0,49	0,42	0,35
Relative humidity		RH %, winter	40-60	30-60	30-70
CO_2		ppm, Room air	800	800	1000
		Intake air	600		

** Equivalent to 0,7; 0,6; 0,5 air changes/hour by 2,5 m floor height*

6.5.4 Safety in use

Aspects with regard to the physical safety of the residents, are treated by prescriptive minimum requirements in the building regulations. These are therefore not relevant in the ILCD comparison between alternatives. In terms of protection for house breaking (mechanical exposure) the highest class according to Table 5.2, can be obtained if external walls of concrete are used at the street level. For the normal residential building application, this is protection class not deemed necessary. However, in order to obtain flexibility for other types of use in the future this kind of consideration may be valid.

6.5.5 Acoustic design

The routine included in the toolbox was applied. Diagram 6.1 shows the results indicating that a floor thickness of 280 mm is necessary to obtain sound class A and 220 mm for sound class B. According to the programme the internal walls between flats should be not more than 40 mm thinner than the slabs, that is minimum 240 mm for class A and 180 mm for class B.

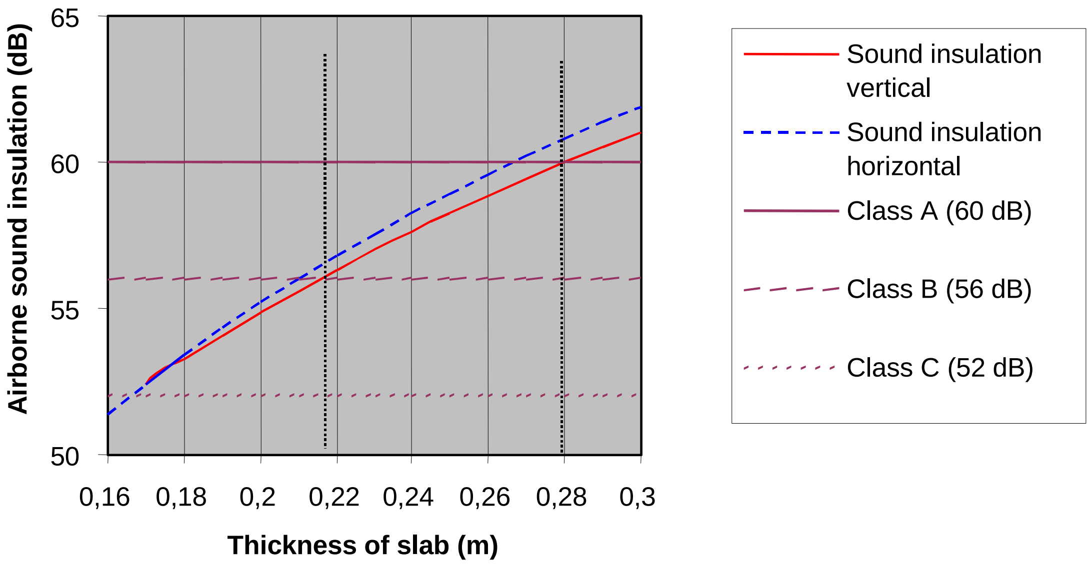


Diagram 6.1 Minimum slab thickness for airborne sound insulation classes A,B and C according to Ljunggren (2000)

6.5.6 Energy design

The energy performance of a building is governed by the technical design and the functional criteria. In this case there is a balance between thermal comfort during summer, air exchange rates and energy efficiency. The BEST building is intended to have the highest ventilation rate and still the lowest energy requirements. Climatic data for Lund 2001 were used for the design.

The energy performance according to Table 6.6 was predicted for the alternatives with the VIP+ programme in the ILCD toolbox.

Table 6.6 Energy balance for the three alternatives plus one additional 'Best available' alternative, cf. Section 4.6, estimated by the VIP+ programme

	Energy used (kWh/m^2,year)					Energy supplied (kWh/m^2,year)			
	Trans-mission	Air leaks	Ventilation	Hot tap water	**** Over-temperatures	Solar radiation	Other free gains	Heat recovery	**Bought energy**
NORM	51	0*	58	34	16	39	44	0	**77**
GOOD	44	6	73	34	17	39	44	33	**59**
BEST	32	6	86	34	15	37	44	39	**55**
Best available	30	7	67	21	16	35	44	38	**33**

** Air leaks computed as fresh ventilation air with mechanical exhaust ventilation (NORM)*

In order to further decrease energy consumption to the 'Best available' class, according to Section 4.6, the following adjustments were made:

- The hot water consumption was reduced by 15 % by water saving white goods.
- Recovery of energy from the wastewater was installed (Efficiency factor 30%).
- Air-exchange rate was reduced from BEST (0,49 L/s, m^2 floor area) to GOOD level (0,42 L/s, m^2 floor area) to decrease ventilation losses.
- Exhaust air heat recovery efficiency was improved from 60% to 80%.

In addition to the calculated energy use for space heating and hot water there is common and domestic electricity consumed. In the criteria in Table 6.1 common electricity is included. According to Section 4.6 this can be estimated to 15 kWh/m^2,year. Adding this to the calculated climate energy use the criteria according to Table 6.1 are met.

The 'Best available' alternative is not included in the following analysis since the added production cost for the specific improvement actions was not examined. The example, however, indicates the potential for energy efficiency improvement with existing technology. An example from Finland, described by Sarja et al. (2003), shows that this low energy strategy may be optimal in the life cycle perspective.

6.5.7 Durability design

This study covers alternative designs with regard primarily to the building frame, and ventilation systems. Durability of ventilation system is estimated by the experienced based method according to Section 4.7. The durability design of the structural frame and balcony, follows the European concrete standard EN 206 (CEN 2000). To present an alternative quantitative probabilistic method, the balcony slab is also designed according to a method for service life design of concrete structures that has been developed by the Swedish Concrete Association (SBF,1998).

The structures are exposed to the following conditions, cf. Section 4.7:

- Dry, heated: The structure inside the climate shield.
- Moderately humid, heated: Bathrooms.
- Saturated or humid and subject to freezing: Balcony slabs.

According to the design life criteria in Table 6.1 the components can be either 'support' or 'infill'. In this case the structural frame always belongs to support while the balcony slab could in principle be defined either as support or infill. In this example the balcony slab is however regarded as support and the design life alternatives are: BEST 180, GOOD 120 or NORM 60 years. The balcony slab is designed for these three service life alternatives. The cost and environmental burden for these are calculated and compared.

<u>Balcony slab</u>
The degradation factors for the balcony slab are carbonation and saturation (exposure class group: XC) relating to reinforcement corrosion and freezing and saturation (exposure class group: XF) that may cause frost damages. In this case exposure classes XC 3 or XC 4 and XF 1 or XF 3 respectively according to EN 206-1 are relevant. The double classification is due to different moisture conditions on top and bottom side of slab.

With regard to frost resistance the concrete composition is decisive, and as the same concrete is used for the entire slab it must be designed according to the harshest class of the two, XF 3. Entrained air pores to a total of 5% percent by volume and a water to cement ratio of maximum 0,55 are thus required.

With regard to reinforcement corrosion (XC) with a water cement ratio of maximum 0,50, the minimum concrete cover to reinforcement is 20 mm, for a design life of 50 years, and 30 for 100 years, (SIS, 2002). With the tolerance of 10 mm, normal for house building, the base cover should be 30 and 40 mm for 50 and 100 years design life respectively. With adequate production control the tolerance may be decreased to 5 mm.

An example of an alternative, quantitative probabilistic, service life design with regard to reinforcement corrosion, for the three design life alternatives 60, 120 and 180 years, is given in Annex 6.D.

Structural frame

The parts of the structure inside the climate shell of a normal Swedish residential building is a 'very dry environment' according to the meaning of the European concrete standard, EN 206-1. The structural frame in this example is thus classified as 'X0'. The exception is bathrooms and laundry rooms, which with moderate humidity are classified as 'XC3' according to EN 206-1. Here the carbonation, that depassifies the steel, may result in reinforcement corrosion.

The material requirements vary significantly between these two exposure classes and it is possible to differentiate between the applications in order to optimise production costs, as bathrooms constitute only a small proportion of the building. However, it may also be of interest for the possibility of future changes in use of the building, to design the whole structure for the harsher XC3 exposure class. In particular for the BEST case, where flexibility in terms of number of flats and thus location of bathrooms was specified in the design brief, cf. Table 6.3.

The rate of carbonation with regard to exposure conditions and material properties is well defined (SBF, 1998). With the method envisaged in Annex 6.D predictions of service lives for different scenarios with regard to carbonation can be undertaken, to support economical and environmental whole life optimisation.

6.5.8 Design with regard to robustness and risk

The combined qualitative/quantitative method according to Section 4.8.3 is applied. The following structures and systems are deemed strategic with regard to robustness of a multi-dwelling building, and are thus analysed with regard to the local climatic and other relevant conditions.

i. Roof. With regard to rainwater and condensation.

An inclined roof with external rainwater drainage is conceived, which is a low risk alternative, with regard to rainwater under any circumstances.

A concrete slab carries thermal insulation and a ventilated roof, cf. Annex 6.A. The slab provides sufficient and durable air tightness. Tightness is particularly important in a relatively high building, where the stack effect, moves warm air upwards. In combination with supply and exhaust ventilation and suction of air on the lee side, inside overpressures occur. Humid indoor air may penetrate the climate shell and condensate.

One aspect that needs further quantitative analysis is the risk of condensation on surfaces in the ventilated space over the thermal insulation. This depends on specific humidity conditions during different seasons and temperature. Increased thermal insulation of the roof leads to low temperatures in the ventilated space above, and thus to increased condensation risks.

ii Exterior walls including connections to windows, interior floors and base with regard to air tightness, moisture conditions, thermal bridges and rain water exposure.

In this case a very well proven solution with brick cladding, air-gap, mineral wool in three layers and either a concrete load bearing inner leave, or a curtain wall construction is proposed, cf. Annex 6.A. Steel studs are proposed in the curtain wall to eliminate any organic materials and related risks. Critical aspects are the vapor-barrier for the curtain wall type, and in particular its connections to adjoining structures. Furthermore the frost resistance of bricks becomes more critical with increased façade insulation thickness.

iii. Slab on ground with regard to ground moisture.

The moisture transport can be predicted by calculation according to Harderup and Harderup (2000) and the thickness of the insulation, placed under the concrete slab, is designed to secure that moisture from the ground is driven downward.

iv. Ventilation system including air intakes with regard to thermal comfort during the heating season and thermal comfort during summer.

Here supply and exhaust ventilation is proposed for all except one alternative. That will secure thermal comfort during winter for those. Summer indoor temperatures are estimated by calculations.

6.5.9 Lifetime functionality and usability design

Objectives are organised according to the three dimensions of flexibility:

A) Service flexibility: 0-1 years.

B) Modifiability: 3-10 years covering movable partitions walls, load changes, adjustment of ventilation meeting foreseeable changes in needs for the users

C) Long-term adaptability: 30- years referring to adaptability in case of unknown future changes.

For NORM: No requirements

For GOOD: Full flexibility with regard to configuration of interior partitioning walls in flats. Possibility to change from residential to shop or office use, on the bottom floor.

For BEST: As GOOD plus possibility to change 10 large flats to 20 small.

6.5.10 Summary technical outline

Table 6.7 presents the technical outline regarding structure, thermal insulation and ventilation system to fulfil the criteria for each alternative according to Table 6.1.

The determining factor for each specific aspect is the following:

- Floor thickness is governed by acoustic requirements for BEST and GOOD and the deflection requirement for NORM.
- Wall thickness is governed by acoustic requirements for all alternatives.
- Floor free height is here determined according to the possibility to use the building for other than residential purposes and, furthermore, to acquire more comfortable and pleasant flats.
- Insulation thickness is here selected according to best practice in Sweden (BEST) and current norm level (GOOD, NORM).
- Ventilation is governed by the indoor climate specification, cf. Table 6.5.
- Heat recovery on exhaust ventilation is an efficient way to reduce the energy consumption in line with the criteria for BEST and GOOD.

Table 6.7 Technical specifications and data of the three alternatives

	Quality level		
Aspect	**BEST**	**GOOD**	**NORM**
Floor thickness (structural), mm	280	240	180
Concrete grade structural floors	C32/40	C40/50	C25/30
Walls separating flats, mm	240	220	160
Slab on ground	120	120	120
Concrete grade walls/grounds slab	C25/30	C25/30	C25/30
Reinforcement struct. Slabs (kg/m^2)	7,4	8	5,1
Reinforcement walls (kg/m^2)	6	6	6
Reinforcement slab on ground (kg/m^2)	3,6	3,6	3,6
Reinforcement cover (mm)	25	20	20
Floor area (m^2)	2496	2496	2496
Load carrying wall area (m^2)	1180	1180	1641
Slab on ground (m^2)	416	416	416
Balcony slab thickness (mm)	215	210	200
Concrete grade balcony slab	C40/50	C40/50	C40/50
Reinforcement/balcony slab (kg/m^2)	7,0	7,0	7,0
Insulation thickness, mm Wall/Roof/Ground	310/500/ 200	200/400/70	160/300/70
U-value, W/m^{2}C°. Windows, doors	1,0	1,4	1,6
Ventilation	Supply and exhaust		Exhaust
Heat recovery on exhaust air	Yes		No

6.6 Life cycle appraisal including modular life cycle planning

In this section the life cycle consequences of the alternative designs are estimated applying the tools for LCC and full LCA in the ILCD toolbox. This part of the work refers to the second cornerstone of ILCD according to Figure 3.3.

6.6.1 Modular life cycle planning

There are three aspects relevant by modular life cycle planning:

a. Total length of life of building
b. Length of life and periodic maintenance of systems and structures.
c. Any changes wanted in systems or structures with regard to changes in use.

<u>a. The total length of life</u> of a Swedish multi-dwelling building is normally more than 100 years, cf. Section 1.1. There are three options with regard to durability defined in Table 6.1: 60, 120 and 180 years. It may be difficult to determine the total life at the design stage. By performing life cycle appraisal for different life spans the question may be resolved. In this case the economical and environmental consequences of the three design alternatives were estimated by the ILCD tool from 30 to 180 years, cf. Table 6.8. The conclusion was that the relation between the alternatives did not differ significantly, why any of the life spans could be used to guide the choice. The calculation horizon could thus be selected to be 100 years to obtain balance between initial and operating costs according to Section 5.11.3.

<u>b. The periodic maintenance</u> module in the LCC spreadsheet is applied to deconstruct and the repackage the building, including systems into groups with coinciding maintenance intervals, cf. Table 7.20. The generic data on maintenance intervals in the tool box were used as the base. These adjusted intervals can be utilized by specification of the particular components. An example of life cycle planning is the balconies, which were analysed with three different design lives. cf. Section 6.7.2. Changes in the use of the building are outlined in the criteria listed in Table 6.1. Here the design of the structure was adapted to suit different configuration of flats, and possible change of use in the bottom floor.

6.6.2 Economical life cycle appraisal

Production costs were estimated by applying a statistical base value for the NORM alternative: 2090 Euro/m^2 or 5011000 Euro total project cost. (SCB 2003). For the other two alternatives BEST and GOOD, extra cost referring to the differences in standard were determined, cf. Annex 6.B. Additional costs compared to NORM are for GOOD: 130000 Euro and for BEST: 206000 Euro. These added costs represent 2,6 and 4,1% increase of total project cost.

Based on the modular life cycle plan and the energy balance calculations for the three alternatives, the LCC module of the ILCD toolbox was used to estimate life cycle costs. Annex 6.C shows the summary page of one calculation (NORM).

Table 6.8 shows how the length of calculation horizon affects the three alternatives. In this case the cost relation between the alternatives changes little, by different calculation horizons. Note the influence of value at end of life. In principle a higher quality should lead to a higher residual value. Therefore it may be relevant to compare the 'identical with initial' values for the 'BEST' with the

'1/2 the initial' values for the 'NORM' alternative. It is not possible to provide any generic conclusion on this. The examples in Table 6.8, however how the possibilities for analysis.

Table 6.8 Annual costs and present value (Euro/m^2) for the three design alternatives with different calculated length of life of building ad with different end of life scenarios

Life span	**BEST**		**GOOD**		**NORM**	
Value at end of life identical with the initial production cost						
years	Euro/m^2, y	Euro/m^2	Euro/m^2, y	Euro/m^2	Euro/m^2,y	Euro/m^2
30	88	1875	88	1865	88	1862
60	93	2960	93	2945	93	2951
90	94	3476	94	3460	93	3470
120	95	3753	94	3738	94	3752
150	95	3893	95	3879	95	3895
Value at end of life ½ the initial production cost						
30	113	2393	112	2375	111	2359
60	101	3207	101	3189	100	3189
90	97	3594	97	3576	97	3583
120	96	3809	96	3793	96	3806
150	96	3919	95	3905	96	3921

For this case a calculation horizon of 100 years was selected and the result of the LCC calculation on the three alternatives is displayed in Table 6.12.

6.6.3 Environmental assessment-production phase

In this case a full LCA is conducted on the concrete building frame with the method compiled in the ILCD toolbox, cf. 5.12.2. The procedure follows the traditional steps of LCA presented in Section 2.5.2.

<u>Goal definition and scooping</u>

The first task is to assess and compare the environmental burden emanating from production of three alternative concrete building frames. The differences between the alternatives are type and amount of concrete and amount of reinforcement in interior concrete walls and slabs. The *functional unit* is selected as one m^2 of floor area, including relevant share of concrete walls, roof slab and slab on ground. The substructure is not included.

The second task is to compare the environmental burden for production of balcony slabs with different design lives. Here the functional unit is one m^2 of slab.

In both cases the environmental burden of 1 kg of the specific concrete, including reinforcement, is computed.

Life cycle inventory

A process tree is drafted with the LCAiT (1996), software, cf. Figure 5.4. Input data sources are displayed in Annex 5.F. The inventory is processed by the LCAiT software, included in the ILCD toolbox. The emissions and resource use for one kg of each specific concrete is computed. The result of the inventory of each 'type concrete' including relevant amount of reinforcement is presented in Table 6.9.

Table 6.9 Inventory results for 1 kg reinforced concrete. The 'type concretes' Cradle to finished structure.

	BEST slab	GOOD slab	NORM slab	Wall	Balcony
Concrete grade	C32/40	C40/50	C25/30	C25/30	C40/50
Reinforcement (kg/m^2)	5,9	6,4	4,1	4,8	7,0
Emissions to air					
NO_x (g/kg)	0,29	0,30	0,26	0,26	0,30
SO_2 (g/kg)	0,07	0,08	0,06	0,06	0,08
CO_2 (kg/kg)	117	123	101	102	126
Energy use (MJ/kg)					
Fossil fuel	0,53	0,55	0,46	0,47	0,56
Electricity	0,25	0,26	0,24	0,24	0,26
Waste fuels	0,14	0,14	0,11	0,11	0,14

Impact assessment

The weighted result of the impact assessment, based on the EPS weighting system, cf. Section 2.5.3, is presented in Table 6.10.

Table 6.10 Environmental burden

	Structural frame			Balcony slab		
	BEST	GOOD	NORM	BEST	GOOD	NORM
Functional unit	m^2 structural frame including walls			m^2 balcony slab		
EPS 2000 (ELU)	15,4	12,5	8,2	11,0	10,6	9,6

The calculated environmental burden relates to the concrete building frame only. In order to clarify the total environmental burden of the project, generic data for production of Swedish multi-dwelling buildings are used together with the added impacts according to Table 4.11. The data on energy requirements referring to a study by Adalberth (2000), are used as a base level, similar to the NORM alternative, which is 820+30+120 kWh/m^2 for materials, transports and building site. It is assumed that half of the materials, and the whole transport refer to fossil energy and the rest to electricity. According to the LCA method in the tool box, the resulting environmental cost is 53 ELU/m^2, which is attached to the NORM alternative. GOOD is given 53 – 8,2 + 12,5 = 57,3 ELU/m^2, and BEST thus 60,2 ELU/m^2.

6.6.4 Environmental assessment - user phase

The environmental assessment module in the ILCD toolkit, described in Section 5.12.1 is applied. The results are presented in Table 6.11. The calculation horizon was set to 60 years. In this case environmental data for average Swedish district heating and electricity are applied.

Table 6.11 Assessment of environmental burden of energy use during operation for 100 years according to the EPS 2000 weighting system

	Quality level			
	Best available	BEST	GOOD	NORM
Space heating (kWh/m^2)	3300	5500	5900	7700
Common electricity (kWh/m^2)	1500	1500	1500	1500
EPS 2000 (ELU)	176	283	302	389

6.6.5 End of life

There are two applicable strategies with regard to end of life:

i. To determine a specific point in time when the life of the building is ended, and calculate the demolition costs or other residual cost. This could possibly be combined with a 'run down' maintenance plan.
ii. To determine a specific point in time where the calculation horizon ends, without any definition of what is physically taking place at that time. This could be combined with an 'eternal' maintenance plan intended to keep the building in its initial shape. In this case a residual value, for instance the same as the new building, could be attached to model a second hand value.

With regard to environmental cost the demolition alternative (i) releases an environmental burden caused by energy use for machinery and transport, and furthermore from disposal of any materials that cannot be recycled or reused. These environmental costs are relatively easy to calculate at the design phase, when types and amounts of materials are known.

In this case the strategy with a residual value of the building is applied (ii). The present value of the initial construction cost is set as a residual value.

6.7 Result summary of the quantitative life cycle appraisal

6.7.1 Whole building

Table 6.12 presents the quantitative life cycle consequences with a calculation horizon of 100 years.
Definition of areas:
Total floor area: 2496 m^2. Total usable floor area 2400 m^2. Net rental floor area: 2280 m^2 of which are flats: 2100 m^2.

Table 6.12 Predicted quantitative results of comparison between alternative quality levels for the building studied.

	Quality level		
Aspect	**BEST**	**GOOD**	**NORM**
Production			
Cost. Euro	5217415	5141064	5010989
Production time	X + 3 weeks	X	X
Environmental burden. ELU***	144480	137520	127200
Functional/Life cycle			
Operating cost. Present value	3888483	3921160	4037083
Environmental burden. ELU	679312	725763	934791
End of life cycle			
Value. Present value Euro	441640	435178	424167
Environmental burden	-	-	-
Total life cycle			
Cost. Present value. Euro	**8664000**	**8627000**	**8654000**
Environmental burden. ELU	**823800**	**863300**	**1062000**
LCC + Environment. Euro/ELU	**9487800**	**9490300**	**9716000**
Total floor area	2400	2400	2400
Net usable floor area (‘NF’)	2020**/2070*	2070*	2100
Total life cycle cost/NF	**4289/4186**	**4168**	**4121**
Total environmental burden/NF	**408/398**	**417**	**506**
(LCC + Environmental burden)/NF	**4697/4583**	**4585**	**4627**

**30 m^2 lost for ducts and installation room with supply and exhaust ventilation and heat recovery*
***50 m^2 lost in case of increased wall insulation and exterior perimeter of building fixed. A fixed perimeter is normally applicable for projects in central locations.*
**** The total environmental burden for the production of 1 m^2 of Swedish multi-dwelling building based on energy requirements according to Adalberth (2000) and includes material, work on and off site and transport. Adjusted for specific differences between alternatives.*

In Table 6.6 the energy balance of a ‘Best available’ energy alternative is also presented. The resulting saving in energy costs compared to the BEST alternative is 180000 Euro, or 75 Euro/m^2. In Table 6.11 the socio-economic revenue is presented, which is: 283 – 107 = 107 ELU/m^2.

6.7.2 Balcony slab

Three alternative design lives were defined; 60, 120 and 180 years. Here the difference in production cost motivated by the lifetime effects with regard to maintenance and environmental burden is computed for three different calculation horizons: 50, 100 and 150 years. The difference with regard to durability is theoretically totally (upper + lower side) 12 mm going from 50 to 100 years and 22 mm years going from 100 to 150 years. In practise the same cover might be used giving 20/30 mm total added cover for 120 and 180 design lives respectively.

According to Hellström (2004) the marginal cost for production, transport and site costs for this type of balcony slab is 190-280 Euro/m^3. Thus 20 mm adds a cost of 3,7-5,6 Euro/m^2 and 30 mm adds 5,6-8,4 Euro/ m^2. For a 5 m^2 balcony the mean extra cost thus is 23 and 35 Euro respectively.

The cost for a 5 m^2 balcony by new production is approximately 1100 Euro. The cost to replace one 5 m^2 concrete balcony in an existing building is 2400 Euro, according to SABO (2001). The environmental cost for a 5 m^2 balcony is 55, 53 or 48 ELU for the 180, 120 and the 60 year service life balconies respectively, cf. Table 6.13.

The total life cycle cost and environmental cost for the three calculation horizons and three design lives are presented in Table 6.13. The table shows that for a 50 year calculation horizon the 60 year balcony is preferred, which is obvious. The differences with regard to cost and environmental burden are, however, very small. With a 100 year horizon the 120 year balcony is profitable but the additional cost to prolong the service life with 50% is very small. This implies that the 120 or the 180 year balcony are the preferred alternatives, by any situation were it is not absolutely certain that the service life is less than 60 years. Even in such a case there is no significant advantage with regard to cost or environmental burden to select the short design life.

Table 6.13 Maintenance and environmental costs according to design life and calculation horizon. Euro/ELU per balcony

Balcony design life (years)	Cost (Euro/balcony)			Environmental burden (ELU/balcony)		
	Calculation horizon (years)			Calculation horizon (years)		
	50	100	150	50	100	150
60	1110	1655	1779	48	96	144
120	1133	1133	1257	53	53	106
180	1145	1145	1145	55	55	55

6.8 Total ranking of alternatives

The multiple attribute ranking aid MADA, presented in Section 5.6 is applied. The lifetime quality of the building expressed by the design brief of Table 6.1 can be presented in the decision tree according to Figure 6.2. Here the relative importance of each attribute is stated, expressed in %. Note that, by aspects such as safety, the rating here expresses how an increased quality level, above the threshold values given by norms, is perceived.

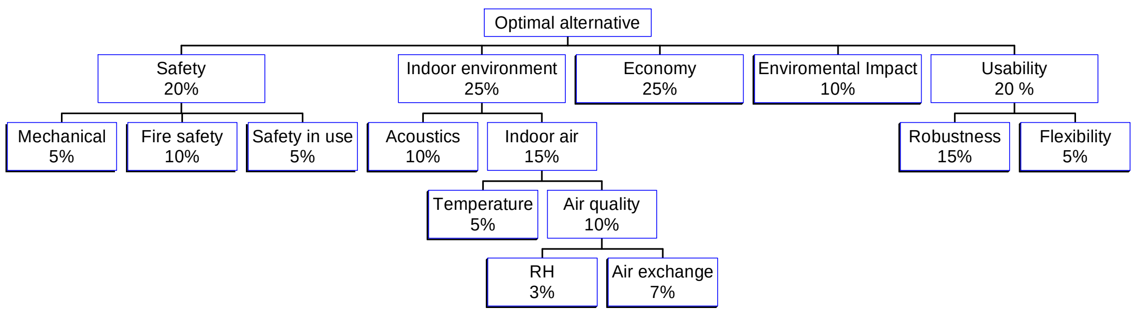


Figure 6.2 Hierarchical tree structure.

In Table 6.14 the results of the pre-design including the life cycle appraisal are presented. In some cases, for example the safety attributes, the structures automatically qualified for a higher quality than the initially intended.

Table 6.14 Decision matrix including predicted performance for the alternatives

Attribute			Alternative			Unit
Level 1	Level 2	Level 3	BEST	GOOD	NORM	
Safety	Mechanical		S1	S1 ~~(S2)~~ *	S1 ~~(S3)~~ *	Stability class
	Fire safety		120	120	120/60	REI
	Safety in use ****		Sk1~~(Sk3)~~	Sk1~~(Sk2)~~	Sk1	Protection class
Indoor Environ-ment	Acoustics		A	B	C	Acoustic class
	Indoor air	Quality	0,49	0,42	0,35	Fresh air flow**
		Temp	15	17	16	Cooling***
Economy			4289/ 4186	4168	4121	Euro/m^2
Environm.			408	417	506	ELU/m^2
Usability	Robustness		1	1 ~~(2)~~ *	1 ~~(3)~~ *	Insurance class
	Flexibility		High	Medium	Moderate	Verbal

* *Automatically qualifies for highest class*
** *Air flows according to Table 6.5. (L/s,*m^2*)*
*** *Theoretical cooling energy to maintain comfort level +27*°C. (kWh/m^2,year)
**** *This classification refers to the protection with regard to house breaking. The alternatives are equivalent from this point of view.*

In Table 6.15 the resulting MADA ranking of the alternatives is displayed. Higher functional quality and lower environmental burden for BEST and GOOD dominates over the somewhat lower cost for the NORM alternative.

Table 6.15 Final ranking of alternatives in the example

	Quality level		
	BEST	**GOOD**	**NORM**
Mechanical	0,05	0,050	0,050
Fire safety	0,10	0,100	0,100
Safety in use	0,05	0,050	0,050
Acoustics	0,10	0,075	0,050
Air exchange	0,07	0,053	0,035
RH	0,03	0,030	0,030
Temp	0,05	0,048	0,049
Economy	0,25	0,257/0,251	0,260/0,254
Environment	0,10	0,098	0,081
Robustness	0,15	0,150	0,150
Flexibility	0,05	0,033	0,017
Sum	**1**	**0,94/0,94**	**0,87/0,87**

6.9 Discussion and conclusions of the desk-top study

This example features the main steps of the ILCD-process according to Section 3.3. The first steps covering investment planning and client need analysis are treated in a simplified hypothetical way by assuming that three alternative performance levels are targeted. The objective of the study is to establish the lifetime cost and environmental burden of the three quality levels. Based on that quantitative assessment together with the functional performance evaluation, the preferable alternative is identified. The feedback step is, however, left out, as there are no production or user phases available to assess.

From a strict cost perspective the 'NORM' alternative is 1 to 1,5% better than the 'GOOD' or 'BEST' alternatives. With a fixed perimeter of the building the difference to the 'BEST' alternative increases to 4%, as some usable floor space is lost for 'BEST' because of thicker insulation. If environmental aspects are added the preferred alternative is 'GOOD'. In the case of a free perimeter of the building the 'BEST' is equivalent to 'GOOD'. Finally, when the functional aspects are added the ranking indicates that the 'BEST' alternative is preferable, followed by 'GOOD'. Note that the author conducted the ranking between attributes. It is however very simple to test other priorities with the ILCD tool. For example, it was found that if the relative importance of economy was increased to approximately 85% the obtained rating, between alternatives according to MADA, became even.

With the ILCD toolbox the lifetime consequences of design options can easily be estimated, and different scenarios can be examined. In this case it was shown that a higher functional quality could be selected for example with regard to ventilation (air-changes) and sound insulation without adding significant lifetime costs or environmental burdens. The alternative 'GOOD' with functional quality in between 'BEST' and 'NORM' is estimated to provide the optimal life cycle cost and environmental burden. However, depending on the required functional quality of the project, and emphasis on environment, the 'BEST' alternative may also be preferred.

The design of the concrete slabs illustrates the importance of a holistic approach to obtain the best solution. The following aspects interact: Mechanical behaviour including deflections, fire safety, sound insulation, durability, concrete drying time and production cost. The variables are: Thickness of slab, concrete composition, reinforcement and furthermore production method.

The balcony slab example indicates that with a small extra effort by production, in this case by increasing the concrete cover, the technical service life can be greatly expanded. This is advantageous both with regard to economy and environment in applications that are intended to last for a long time, such as the primary structures of permanent multi-dwelling buildings, cf. Section 3.3.6.

The possibility to enhance energy performance to reach the 'BAT' class according to Section 4.6 was investigated. It was shown that this was possible with relatively simple technical measures. The resulting improvement with regard to the environmental burden, and operating cost of the building was also estimated.

7 INTEGRATED LIFE CYCLE DESIGN – APPLICATION EXAMPLES

This chapter presents tests of the ILCD toolbox presented in Chapter 5 on a number of real projects. The objectives of these tests were (A) to:

- Examine and illustrate different applications of ILCD.
- Quantify the potential improvements with regard to whole life quality of dwelling buildings that can be achieved with ILCD.
- Test and refine the simplified ILCD toolbox that has been developed.

Furthermore the examples were utilised to (B) map:

- To what extent the parties involved in the specific projects address ILCD aspects in their current practice.
- Barriers and drivers for ILCD.
- The potential value of ILCD for the client.

ILCD covers different activities in the design process as described in Section 3.3. In Table 8.1 the application examples, described below, are sorted into the pertinent phase in the ILCD process.

7.1 Overview of method and presentation of results

ILCD was tested on eight different cases representing various phases in the projects, from early planning to follow up. The particular task in each project differed, and is explained below, for each case. The projects were undertaken from the end of 2002 until the summer of 2004 and are reported in chronological order. Internal reports were compiled for each project. Some of the application examples have also been presented as contributions to conferences.

The work was conducted in collaboration with the parties involved in the specific project, and was thus participative from the research methodological point of view.

This chapter primarily presents the quantitative and methodological findings referring to the first three objectives (A) while the results relating to the second three items (B) are discussed and synthesised in Chapter 8. To collect information regarding (B), personal interviews were conducted with a standardized questionnaire as a base, cf. Annex 8.A.

7.2 Example A

Example A is presented in an internal report for the project team (Öberg 2003-A) and by Öberg (2003).

7.2.1 Background

The project comprised the production of four new 26-flat, multi-story dwelling blocks in the city of Malmö in South Sweden, cf. Figure 7.1. The original design of the structure consists of cast in place concrete on prefabricated floor slabs. Prefabricated lightweight aggregate concrete interior walls elements and rendered aerated lightweight concrete block façades. The building is heated by district heating via water radiators and has mechanical exhaust ventilation.

Figure 7.1 Façade of application example A. Sketch with permission from the architect: Marie Ericsson, Plan och Byggnadskonst Arkitekt AB, Lund.

The client is a nationwide organisation for housing co-operatives. The works were procured on a modified design and build contract, whereby the client is relatively closely involved in the design process. A major Swedish construction company executed the works, and a team of local consultants were engaged for the design. The production was divided into two phases with two identical blocks each.

The production of the first phase commenced in December 2002. For the second phase, the client wanted to examine some alternative technical solutions, and the author of this thesis was invited to compare those with the original design from a life cycle perspective.

7.2.2 Task

The task was to evaluate the life cycle consequences of alternative designs with regard to façade and ventilation system for phase two of the project. The alternatives were:

- Curtain wall brick façade carried by steel columns (F II) instead of massive block walls (F I)
- Supply and exhaust ventilation with heat recovery (Vent II) instead of mechanical exhaust ventilation (Vent I)

7.2.3 Method

A quantitative analysis of life cycle consequences over a life cycle, defined as 60 years, for the different design alternatives was carried out with parts of the ILCD toolbox described in Chapter 5. The VIP+ programme was applied for the energy balance calculations. Differences with regard to energy use and periodic maintenance were taken into account, as well as loss of usable area.

To investigate to what extent the ILCD aspects were addressed in this particular project a qualitative survey amongst the design team was conducted. The survey comprised the questions according to Annex 8.A, and was undertaken by personal interviews.

The work was started with a half-day seminar on ILCD hosted by the client, and given to the project team by the researcher.

7.2.4 Life cycle appraisal of alternative designs – costs and environmental burdens

In Table 7.1 the results of the quantitative assessment are presented as the difference to the original design (F I/Vent I), which is the reference. In Annex 7.A input data and results are tabled. The present value of life cycle costs based on 60 years calculation horizon was approximately 3000 Euro/m^2, for the reference alternative.

The cost categories that were affected were construction costs, periodic maintenance and heating. For the ventilation system also electricity required for operation of fans differed. With supply and exhaust ventilation some usable area was lost, as more space was required for the ducts and apparatus than by exhaust ventilation.

Table 7.1 Difference in life cycle cost (Euro) and socio economic cost (ELU) per/m² dwelling space over 60 years. Original design (F I/Vent I) as reference.

	Design alternative			
Ventilation	Vent I[c]		Vent II[d]	
Façade	F I[a]	F II[b]	F I[a]	F II[b]
Production cost	-	-19	21	2
Periodic maintenance	-	-3	13	10
Heating	-	-9	-91	-92
Electricity for fans	-	0	8	8
Loss of usable area	-	0	31	31
Sum life cycle cost	-	-31	-17	-41
Socio-economic cost	-	-8	-73	-78
Total difference	**-**	**-39**	**-90**	**-119**

[a] Aerated lightweight concrete block façade, [b] Curtain wall brick façade on steel framework, [c] Mechanical exhaust ventilation, [d] Supply and exhaust ventilation with heat recovery

Sensitivity analyses on energy price increases were conducted, cf. Diagram 7.1. The Vent II ventilation system with higher initial costs and maintenance costs, which should be balanced against lower future heating cost, is more sensitive to the future development of the energy price than the original (Vent I) design.

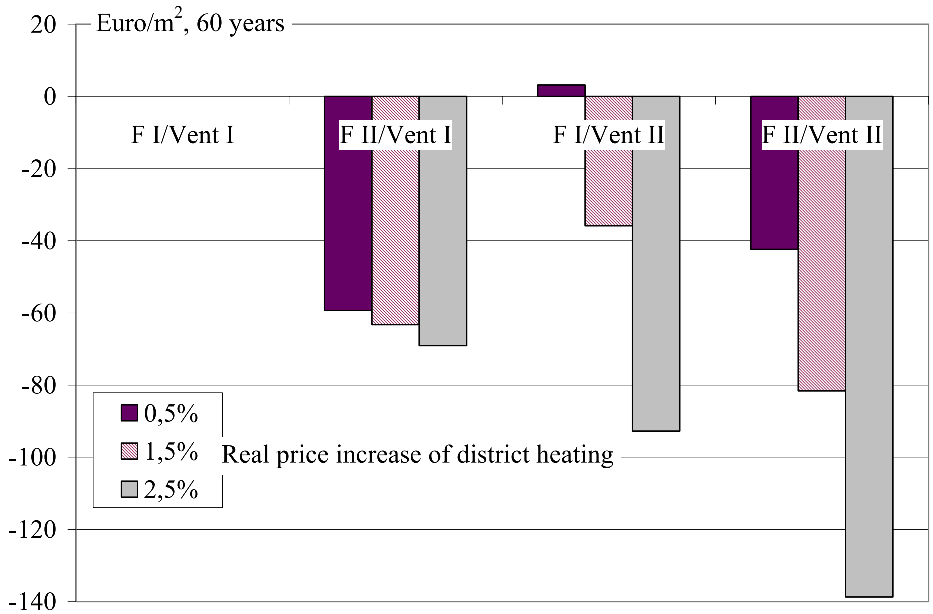


Diagram 7.1 Sensitivity analysis on difference of life cycle cost, in relation to the reference alternative, by different development of energy price.

The differences between alternatives must be viewed in the overall cost perspective. If the costs presented in Table 7.1 are divided by the total life cycle cost 3000 Euro/m^2 and the total Socio-Economic life cycle cost 345 Euro/m^2 respectively the relations in Table 7.2 occurs. Bearing in mind data and model uncertainties, this comparison indicates that, from a strict life cycle economical point of view, the alternatives are equivalent. From the environmental point of view changing to the alternative ventilation system is advantageous (20% improvement), while changing the façade has a minor effect (2% improvement).

Table 7.2 Relative difference between original (reference) and alternative design.

Ventilation	Vent I		Vent II	
Façade	F I	F II	F I	F II
Sum life cycle cost	-	-1,0%	-0,6%	-1,4%
Socio-economic cost	-	-2%	-21%	-23%

7.2.5 Life cycle appraisal of alternative designs – functional quality aspects

When comparing the alternatives with regard to the functional attributes of the ILCD criteria, presented in Table 5.2, it was concluded that there were only the following differences:

- Attribute 3. Indoor environment. Experience indicates that Vent II is preferred with regard to thermal comfort during the heating season, cf. Annex 4.A.2, Diagram 4.A.2.
- Attribute 5. Acoustics. FI and FII possibly provide somewhat different sound insulation towards the outside. The neighbourhood is relatively quiet why any performance difference is deemed irrelevant.
- Attribute 6. Energy use. This is addressed quantitatively Section 7.2.4.
- Attribute 10. Architectural. The FI, rendered façade, was the original proposition and preference by the city-planning authorities. The aesthetical propriety of changing facades for the two remaining of the group four houses was never further examined.

It was therefore not deemed relevant to perform any MADA analysis at this stage of the project.

7.2.6 ILCD findings

The qualitative survey on consideration of lifetime aspects within the project group was conducted based on the questionnaire in Annex 8.A. The results were grouped according to the cornerstones of ILCD in Section 3.3, Figure 3.3. Answers to the specific questions are tabled in Annex 8.A.

<u>No 1: Analyses of client's (residents and owner) needs:</u> This was based on the client's long experience of the performance of materials and systems available, and profound understanding of the local housing market. Furthermore, the city planners also influenced the decisions with regard to external appearance of the

building. No systematic routine to transform the requirements to the technical specification of the building was employed.
No 2: Life cycle appraisal. Materials and systems were selected on the basis of experience of the developer, design team and contractor. No quantifications were made, neither in regard to economy, or global environment. To guide facilities management, a comprehensive maintenance manual is compiled including maintenance actions and intervals, for the specific materials and systems in the building. This is done after the completion, and is thus not a design activity.
No 3: Ranking of alternatives was made in regard to production cost. In this case the extra cost with regard to redesign and changing of production system falls on the alternative design proposed.
No 4: Follow up and feedback from the production phase was in this case systematically organised within the framework of specific development project (Boverket, 2004). There was however a consensus among the design team that this is a general improvement area for the sector.

The client plans a qualitative survey on indoor climate directed to residents, to be conducted the second year after occupancy.

7.2.7 Discussion

The life cycle appraisal indicated that the new façade alternative did not provide any significant difference in terms of life cycle economy. The alternative with supply and exhaust ventilation and heat recovery is clearly environmentally advantageous but gives no strong total economical impact, unless the energy prices will increase heavily.

Because of costs for redesign and for loss of repetition advantages in the production of phase 2, it was decided to hold on to the original alternative. These aspects would not have discriminated the alternative designs if ILCD had been applied from the early design phase. Different technical alternatives might thus have been chosen, in this case mainly decreasing the environmental burden of the building and possibly improving thermal comfort during the heating season.

The importance of a holistic analysis can be illustrated by the finding that there was a relation between performance of ventilation system and façade type. The importance of an airtight façade with regard to energy economy was larger with supply and exhaust ventilation than by mechanical exhaust ventilation. For the case with exhaust ventilation the curtain wall brick façade provided better energy economy because of better U-value. With supply and exhaust ventilation this difference is partly equalised by the better air tightness of the massive block façade, cf Annex 7.A, Table 7.A.5. Furthermore, the air-tightness is also more important with supply and exhaust ventilation, cf. Section 4.8.2.

Benefits with regard to global environment can be difficult to appreciate, since they provide no direct extra value for the client or residents.

Life cycle aspects were not systematically considered in the design work. The client had however vast experience and knowledge with regard to long-term performance of materials, systems and technical solutions, and was thus able to establish and communicate an adequate project programme to the design team and contractor. The client was also very actively engaged throughout the whole process. The contractor together with the client, architect and structural designer were able to develop a very efficient building layout and structural concept with regard to production. This was further to efficient planning of the construction logistics and good climatic conditions during production the explanation for the comparably low project costs (Boverket 2004, p 23).

7.3 Example B

Example B is presented in an internal report for the block producer (Öberg, 2004-B).

7.3.1 Background

The project is a two family detached house on the outskirts of Stockholm with a total of 250 m^2 net floor space, cf. Figure 7.2. This building has a massive masonry façade of 400 mm thick lightweight aggregate concrete blocks with rendering. This façade is currently relatively unusual for detached houses in Sweden, which normally have a timber framework and 150 to 250 mm of thermal insulation. The building furthermore has lightweight aggregate floor slabs instead of the more frequently used timber girder floor. The building was completed in 1999. The residents have appreciated the good thermal comfort and low energy costs.

A question raised is if this type of massive structure has comparable energy performance in relation to a conventional timber frame structure, even though the elemental U-values are significantly lower in the timber frame façade. The manufacturer sees a risk in that design criteria in building regulations relying primarily on the elemental U-value unjustly disqualifies the massive block exterior wall. See further discussion on energy performance ('EP') assessment approaches in Section 4.6.2. It is expected that aspects such as thermal storage and air tightness of the massive block wall to some extent balances the higher U-value with regard to overall energy performance of the building. An insulated 'sandwich' block, is also available from the manufacturer, and is included in the study.

With different physical characteristics of the climate shell it was furthermore questioned if interaction between type of ventilation and structure may have any significance with regard to total energy performance.

Figure 7.2 Example B. Façades towards the East and South. Photos with permission from the Maxit Group.

7.3.2 Task

The manufacturer of lightweight aggregate concrete blocks and floor slabs wanted:

- To assess life cycle performance, and in particular energy requirements, of the massive type of building in comparison with a conventional Swedish detached house type.
- To examine a façade of sandwich blocks with a layer of polyurethane insulation between the outer and inner leaves of lightweight aggregate concrete.
- To examine how the massive façade relates to the energy requirements of current Swedish building regulations.

7.3.3 Method

The three structural design alternatives with identical geometry were drafted, based on the original architect drawings, see Table 7.3. For detailed description of input data see Annex 7.B.

Table 7.3 Façade type overview

	Type of façade and internal structure of building	Façade U-value $W/m^{2\circ}C$	Façade air-tightness*
S1	Massive block walls and floor slabs of lightweight aggregate concrete	0,37	1,5
S2	Light timber frame and wood panel façade	0,21	3
S3	Sandwich block façade isolated by 130 mm polyurethane. Massive block interior walls and floor slabs of lightweight aggregate concrete	0,19	1,5

** Assumed m^3/m^2,h at 50 Pa pressure difference*

Two different ventilation systems were examined: Mechanical exhaust ventilation, 'V1', and supply and exhaust ventilation with heat recovery of exhaust air, 'V2'. Energy balance calculations and prediction of indoor climate conditions were undertaken with the energy calculation routine in the ILCD toolbox. Socio-economic costs related to environmental effects of energy use were calculated with the simplified method presented in Section 5.12.1. The operating costs were estimated, and life cycle costs were calculated as present value. The items differing between the alternative designs were costs for energy, periodic maintenance and insurance. One important item missing in this analysis is the construction cost. This is a 'one-off' designed project and the alternative structural solution was not considered by the time of construction, why production cost for that alternative, were thus never estimated. 60 years is applied as calculation horizon in this case. As no production cost is taken into account in this case, the length of the life cycle by calculation becomes less critical.

7.3.4 Energy use for operation and compliance with relevant Swedish requirements

The estimated energy use was 29300 kWh/year or 116 kWh/m^2,year for the massive wall building with no heat recovery on exhaust air (S1/V1), cf. Table 7.4. The average measured energy use for the first 4 years of use of the building was 36000 kWh/year or 143 kWh/m^2,year. All figures include hot tap water. The discrepancy between measured and calculated energy use can to some extent be explained by the increased energy consumption during the first year of operation of a building, as additional energy is required when new building materials are dried out. The average annual energy consumption in modern Swedish dwelling building is 140 kWh/m^2,year according to Section 4.6.3.

According to the elemental U-value approach in the Swedish building regulations, cf. Section 4.6.2, the S1 alternative does not comply with the energy requirements. The maximum acceptable average U-value calculated as 0,18 + 0,95 x (Window area/Total envelope area) [W/m^2K], according to Section 4.6.2, is 0,266, which should be compared with the actual 0,293. That is a difference of 10%. However, if the actual value exceeds the maximum average with less than 30% it is possible to show compliance according to an EP requirement including also other energy characteristics than transmission.

In the first part of Table 7.4 the EP assessment is presented. This is based on energy balance calculation with the VIP+ energy balance programme, which is included in the ILCD toolbox. The results indicate that the S1 alternative exceeds the requirement by 4% or 5 kWh/m^2, year. The difference is small and can be explained by the large window area, compare Figure 7.2.

Table 7.4 Calculated energy balance for alternative designs.

	Energy used (kWh/m^2)					Energy supplied (kWh/m^2)			
	Trans-mission	Air leaks	Ventilation	Hot tap water	**** Over-temperatures	Solar radiation	Other free gains	Heat recovery	**Bought energy**
Energy performance (EP) compliance according to Swedish building regulations									
S1/V1n**	107	0*	63	32	32	87	44		**103**
S2/V1n**	98	1*	63	32	35	87	44		**98**
Ref.***	85	13	62	32	34	87	44		**96**
Calculated energy balance of alternative designs									
S1/V1	115	0*	67	32	32	87	44		**116**
S2/V1	105	1*	67	32	35	87	44		**110**
S3/V1	101	0*	67	32	34	87	44		**104**
S1/V2	114	10	66	32	31	87	29	44	**96**
S2/V2	104	15	67	32	33	87	29	44	**93**

** Air leaks computed as fresh ventilation air with mechanical exhaust ventilation*
*** Calculation with 20ºC indoor temperature to assess compliance with maximum required energy use according to EP criteria in building regulations. See Section 4.6.*
**** Reference building according to EP criteria.*
***** Theoretical cooling requirement to keep indoor temperature comfort level +27ºC*

For the EP assessment an indoor temperature of 20ºC is applied. In a Swedish residential building 22ºC is a more realistic indoor temperature, which is assumed for the 'real' case calculations, presented in the second part of Table 7.4. This explains the lower energy consumption by the EP-calculation.

7.3.5 Life cycle costs and environmental burdens

The periodic maintenance was quantified. For a façade with rendering on massive blocks the service life is estimated to 45 years and after that a repair after 20 years. The repair cost is 23 Euro/m^2, façade. Wood panel façade requires repaint in average every 7-8 years and the total service life is 35 years. The repaint cost is 7 Euro/m^2, façade. (SABO, 2001).

Insurance costs are related to the type of structure. The massive LECA building is according to the Swedish classification defined as a class 1 building (stone) while the all timber house is a type 2,5 building (modern timber). This is reflected in a difference regarding insurance rates with a factor 1,75. REPAB (2000).

The results of the total quantitative analysis, performed with the LCC and simplified environmental assessment tools in the ILCD toolbox, are presented in Table 7.5. Note that the study deals with operating performance, and that the production cost is not included.

From the total cost point of view the results can be used to indicate what difference in investment cost could be justified by differences in operating costs. In this case the operating costs are favourable for the massive frame in comparison with timber frame. Supply and exhaust ventilation with heat recovery is favourable in comparison with mechanical exhaust ventilation.

Excluding production aspects the S2 alternative is favourable in comparison with S1 building from the environmental point of view because of better insulation while the S3 alternative is slightly better than the S2, in the V1 case. For the V2 case with heat recovery on exhaust air the difference in energy performance between S1 and S2 is very small, and the energy performance, and thus the environmental burden, can be regarded as equivalent.

Table 7.5 Predicted life cycle cost and environmental cost, excluding production cost for the different alternatives. Present value Euro/m^2 .

Ventilation	V1			V2	
Structure	S1	S2	S3	S1	S2
Periodic maintenance	163	190	163	175	202
Electricity	152	152	152	156	156
Insurance	34	59	34	34	59
Heating	301	286	270	249	241
Sum life cycle cost	650	687	619	614	658
Socio-economic cost	207	199	191	182	178
Total cost	857	886	810	796	836

7.3.6 Life cycle appraisal of alternative designs – functional quality aspects

When comparing the alternatives with regard to the functional attributes of the ILCD criteria, presented in Table 5.2, the following aspects differ between the alternatives: Fire safety, indoor climate, durability, robustness and architecture.

Indoor temperatures during summer depend on the internal and solar gains, and the energy related characteristics of the building. In Table 7.4 the theoretical energy requirement to maintain a specific maximum indoor temperature, in this case selected to +27ºC, is presented in the column 'overtemperatures'. For the V1 case the massive S1 building has 9% lower overtemperatures than the S2 building, while the difference is smaller, 6,5% by supply and exhaust ventilation (V2).

Comfort problems with indoor temperatures during winter are normally related to draught sensation, which can occur because of insufficient air tightness of the climate shell, and also because of poorly designed air intakes when mechanical exhaust ventilation is used, c.f. Annex 4.A.2, Diagram 4.A.2. Therefore, the supply and exhaust ventilation (V2) system is preferred.

Durability. According to Section 5.9 the service lives of the façade types differ. This is however taken into account by the estimation made of periodic maintenance in the life cycle cost calculation.

Robustness Referring to Section 5.8 the mechanical exhaust ventilation system is more robust with regard to operation, and with regard to the risk of internal over-pressures. The inorganic exterior block wall is more robust with regard to condensation and related risks. The lightweight aggregate structure is furthermore more robust with regard to water and fire accidents, but this is already considered in terms of insurance costs in the life cycle cost calculation.

Architecture. The architectural possibilities of the two alternatives are not discussed here.

7.3.7 ILCD findings and discussion

In the ILCD process, compare Figure 3.3, this example can be referred as part II, life cycle appraisal.

The comparison of the user phase performance between the masonry and the traditional type of structure indicates that periodic maintenance and insurance costs are favourable for the massive block façade. Regarding energy performance, and thus environmental burden, the traditional façade is preferable in combination with the mechanical exhaust ventilation system. The concepts are equivalent for the case with supply and exhaust ventilation with heat recovery on exhaust air. The alternative with sandwich blocks is advantageous by both ventilating systems.

Thermal comfort during summer is somewhat better in the massive alternatives. The difference is 6-9% expressed as theoretical requirement of cooling energy.

The primary advantage of the massive block structure is robustness relating to several aspects. Note that construction costs are not included in this comparison.

The answer to the question if the total energy performance of a building with the massive wall, with rather high U-value, is underrated from the building regulation point of view was that:

- With the elemental U-value approach the average U-value exceeds the regulation with 10%.
- With the EP-approach, energy balance calculation, the difference is decreased to 5%.
- Comparing measured energy use with the average energy use for new residential buildings show no difference.

The conclusion is that for the massive structure aspects, other than the elemental U-value, contribute to the total energy performance. The EP-approach is thus more relevant to assess conformity with norms in such a case.

As in the previous example (A), interaction between climate shell and ventilation system was indicated. Air tightness apparently pays of with a supply and exhaust ventilation system but does hardly affect energy economy with the mechanical exhaust ventilation system. Note, however, that air tightness is in any case important with regard to indoor climate, cf. Section 4.3.4.

7.4 Example C

Example C is presented in an internal report for the project team (Öberg ,2004-C) and in Öberg (2004:2).

7.4.1 Background

The client is a repeat order, semi-public, housing company in a community close to Stockholm. The company has ambitions to provide good quality living at low cost, with low environmental burden, and was therefore interested to look into methods for whole life appraisal. The researcher was invited to perform ILCD analysis on a project comprising 15 units of 4-family buildings, which was in the bidding phase. The objective of the ILCD analysis was to compare the functional and quantitative lifetime consequences of alternative offers on the tender.

The tender had been organised as a design and build contract with a prescribed very high energy standard, comprising heat recovery on exhaust air and very low elemental U-values. A timber frame had been proposed, but other alternatives could also be considered. Figure 7.3 displays one of the 4-family buildings during construction.

Figure 7.3 Example C during construction. Structural frame to the right. Photos by the author.

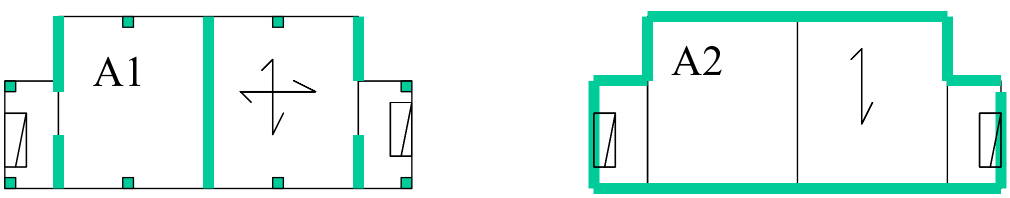
7.4.2 Task

The task was to:

- Design structural alternatives, and assess the overall performance and economy of these, and the original tender design from a holistic life cycle perspective.
- Study how ILCD can aid overall optimisation.

7.4.3 Method

The researcher outlined alternative structural designs with identical geometry as the tender specification. See Figure 7.4.



Cast in place on precast floor slabs. Lightweight curtain wall facades with steel studs

Precast hollow core slabs. Loadbearing concrete sandwich wall facades

Figure 7.4 Floor plans indicating structural principles for alternative designs A1 and A2 outlined for project C. Arrows indicate load-bearing direction.

Energy balance calculations and prediction of indoor climate conditions were undertaken with the energy calculation routine in the toolbox. Socio-economic costs related to environmental effects of energy use were calculated with the simplified method presented in Section 5.4.1. The operating costs were estimated, and life cycle cost was calculated as present value.

The original tender design (OT) was a typical Swedish timber frame building with similar geometry and façade materials, including thermal insulation, as the A1 alternative.

Optimisation was undertaken with the MADA routine, for ranking of alternatives described in Section 5.14. The functional criteria were derived from the criteria matrix presented in Table 5.2.

The researcher communicated the findings to the client through the phase of evaluation of tenders.

After a first overview of the different design solutions, the client requested the competing construction companies to provide an alternative offer corresponding to the A1 proposal. The A2 alternative was not realistic at that stage because of the time needed for re-planning to shift to a prefabricated concrete alternative.

7.4.4 Life cycle appraisal of alternative designs - quantitative results

With regard to life cycle cost and environmental burden the items differing between the alternative designs were:

- Energy use.
- Periodic maintenance.
- Insurance.
- Construction cost.

Elemental energy-data, such as U-values and specific air tightness, relevant for prediction of energy requirements, were in principle identical in the two concepts: Original tender design, 'OT' and A1. Insulation thickness and U-values on windows represent in principle the best available current level in Sweden, with for instance U-value 0,13 W/m^2K on walls, and 1,0 W/m^2K on windows. In A2 the U-value of the wall was 0,21 W/m^2K because of technical limits of thickness of insulation in concrete sandwich walls. On the other hand are load bearing concrete sandwich walls slightly more air tight than light weight curtain wall façades; 1,5 compared to 2 m^3/m^2,h at 50 Pa pressure difference. The result of the energy balance calculations is presented in Table 7.6.

Table 7.6 Predicted energy balance of alternative designs of project C; cf. Annex 7.C, (Öberg 2004:2)

	Energy losses (kWh/m^2,year)					Energy supply (kWh/m^2,year)			
Alternative	Trans-mission	Air leaks	Ventilation	Hot tap water	Overtemp *	Solar gains	Other free gains	Heat recovery	**Bought energy**
OT	75	10	75	43	24	69	32	47	**81**
A1	74	9	75	43	22	69	35	47	**78**
A2	80	8	75	43	21	69	32	47	**82**

** Theoretical cooling energy required when indoor temperatures reach a comfort level.*

Effect requirements for the OT and A1 alternatives were determined indirectly by computing the outdoor design temperature, cf. Annex 7.C, Table 7.C.4. The difference is significant. The lifetime consequences of this were not estimated but it assumed that the required effect for heating becomes very low in the well-insulated, heavy building, alternative. No other heat source than the recovered ventilation air should in principle be needed.

The calculated life cycle cost and socio-economic cost, relevant for comparison between the OT and A1, are displayed in Table 7.7. No sharp tender was received for the A2 alternative, why the production cost for that cannot be tabled.

Table 7.7 Life cycle cost and socio economic cost for 60 years, for original, 'OT', and alternative designs, A1 and A2, cf. Annex 7.A. Note that only the costs categories that differ between the alternatives are displayed.

	OT	A1	A2
Production cost (Euro/m^2)	1780	1800	*
Periodic maintenance (Euro/m^2)	321	321	315
Insurance (Euro/m^2)	17	10	10
Heating incl. hot water (Euro/m^2)	212	205	214
Sum	2330	2337	-
Socio-economic cost 60 years (ELU/m^2)	285	277	288
Life cycle cost including socio-economy	**2615**	**2614**	**-**

** For A 2 no production cost was determined*

7.4.5 Functional performance assessment and optimisation

The functional criteria selected to evaluate the alternatives follow the criteria matrix presented in Table 5.2, with some adjustments wanted by the client. The criteria are organised in a MADA (ASTM, 1998) hierarchical decision tree structure, cf. Figure 7.5. From the tree a decision matrix according to Table 7.8 is developed.

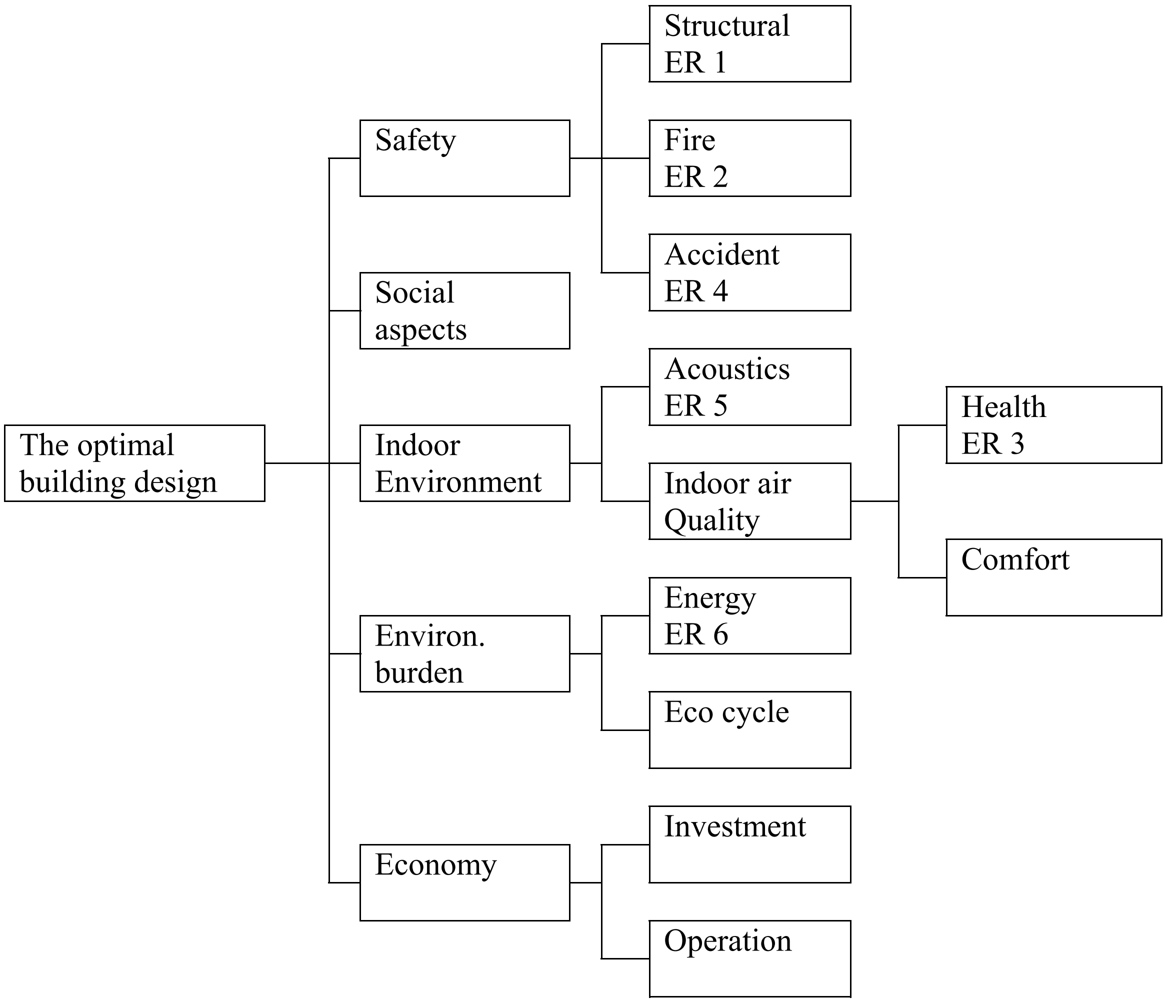


Figure 7.5 Hierarchical tree structure according to ASTM(1998) with criteria for selection of the preferred alternative of the outlined designs. (ER: Essential requirements according to the EU: Construction Products Directive).

Table 7.8 Decision matrix including predicted performance for the alternatives

Attribute						Performance for alternative		
Level 1	W.%	Level 2	W.%	Level 3	W.%	OT	A1	Unit
Safety	10	Structural	3			80	50	Utilisation %
		Fire	4			60	120	REI
		Accident	3			Equal		Risk level %
Architecture	10	Aesthetics	10			Equal		Qualitative
Indoor environment	25	Acoustics	15			C	BC	Sound class
		Indoor air	10	Health	6	30	10	Risk level %
				Comfort	4	2185	1970	Hours > +27ºC
Global environment	25	Energy	80			81	78	kWh/m^2,year
		Ecocycle	20			Equal		Recycling/reuse
Economy	30	Investment	15			1780	1800	$Euro/m^2$
		Operation	15			1128	1112	$Euro/m^2$. Pres.val.

The result of the MADA ranking based on the weighted, digitalisation and pairwise comparisons is displayed in Table 7.9

Table 7.9 Result of ranking of alternatives according to the MADA method.

Weighted rating. High value is better than low. OT, which is the original tender design, is the reference in this case and the values for OT are equal to the importance set for that attribute. The total score for OT is thus 1,0		OT	A1
	Structural	0,03	0,04
	Fire	0,04	0,05
	Accidents	0,03	0,03
	Aesthetics	0,10	0,10
	Acoustics	0,15	0,18
	Health	0,06	0,07
	Comfort	0,04	0,045
	Energy	0,20	0,204
	Ecocycle	0,05	0,05
	Investment	0,15	0,148
	Operating cost	0,15	0,152
	Total score	1	1,07

7.4.6 ILCD findings and discussion

The A1 alternative was selected. The differences between OT and A1 with regard both to initial and operating costs were deemed insignificant. This was due to the fact that they had the same type of façade surface; rendering on insulation, and the same high standard regarding energy performance. Furthermore the difference in production cost was low. Decisive was instead the functional performance, whereby A1 was favourable. In particular the client appreciated the robustness with regard to indoor climate and water damage. The decision was based on a general qualitative assessment of the alternative designs, rather than a result of the

MADA analysis. However, the systematic organisation of attributes and criteria according to the decision matrix, cf. Table 7.8, was appreciated as an assessment aid. The very low effect requirements of the A1 alternative could possibly be further utilized.

The construction work started in June 2004. The project will be followed up with regard to energy performance and indoor climate.

7.5 Example D

Example D is presented in an internal report for the client (Öberg, 2004-D).

7.5.1 Background

This case refers to the same client as example C. As by example C ambitious objectives with regard to energy performance was also applied here, in practice corresponding to the best current practice. The construction of project D was finalized during the time of this work. The client was interested in a general, whole life evaluation of the building, and furthermore to investigate the consequences with regard high indoor temperatures during summer in a very highly insulated building, such as this. The building is a multi-story dwelling block with a total of 21 flats and 1716 m^2 net floor space. Compare Figure 7.6.

Figure 7.6 Example D. Façades facing to the East and North. Photo by the author.

7.5.2 Task

The task was to provide a general whole life evaluation of the building that was under construction, and to assess thermal comfort during summer.

7.5.3 Method

A quantitative analysis of life cycle consequences over a life cycle defined as 60 years, for the different design alternatives, was carried out with the ILCD toolbox described in Chapter 5. The most critical flats with regard to thermal comfort during summer, located on the top floor facing to the Southwest, were assessed specifically.

It was not deemed relevant to perform any comparison with MADA, as there was no decision situation at hand, since the building was already under finalisation.

7.5.4 Life cycle appraisal of the building

The result of the life cycle cost and energy use calculations conducted with the ILCD toolbox are displayed in Table 7.10. Input data are tabled in Annex 7.D. For comparison the average costs within the entire building stock owned by the client are also tabled. The total building stock comprises 4500 flats and 317000 m^2.

Table 7.10 Predicted life cycle costs for example D compared to average costs for the entire building stock of the client. 60 years calculation horizon.

Cost item	Present value	Annual cost	*Average**
	Euro/m^2	Euro/m^2	*Euro/m^2*
Administration	194	6	*12*
Caretaking	217	7	
Water and sewage	85	3	*7*
Electricity (common)	71	2	
Waste disposal	26	1	
Heating	208	5	*11*
Insurance	17	1	*6*
Miscellanous	65	2	
Periodic maintenance	410	13	*13*
Sum	1293	40	*49*
Capital costs***	-	-	*35*
Property tax	78	3	*3*
Total	**-**	**-**	***87***

** Average costs for total stock of the housing company*

7.5.5 Energy use during operation

The results of the calculation of energy requirements during operations with the VIP+ programme are presented in Table 7.11. The results are similar to those of project C, presented in Table 7.6, which had equivalent energy performance objectives.

Table 7.11 Predicted energy balance of project D.

	Energy losses (kWh/m²,year)					Energy supply (kWh/m²,year)			
	Trans-mission	Air leaks	Ventilation	Hot tap water	Overtemp *	Solar gains	Other free gains	Heat recovery	**Bought energy**
	68	5	84	40	27	62	35	49	**80**
Top floor flat	68	10	79	43	20	68	35	35	**83**

* *Theoretical cooling energy required to maintain comfort level of +28°*

7.5.6 Thermal comfort

For the winter case, the building is expected to function well. Experience of modern Swedish residential buildings show that supply and exhaust ventilation, with preheating of the intake air such as in this project, are rated better than mechanical exhaust ventilation system with regard to thermal comfort during the heating season, cf. Annex 4.A.2, Diagram 4.A.2.

Good thermal insulation implies that losses are small. In combination with large energy gains, for instance, from solar radiation through large windows facing to the South and Southwest, there is a risk of uncomfortable temperatures during summer. This was examined with the VIP+ energy balance programme, which is included in the ILCD toolbox.

A maximum temperature is set, here +28ºC. This reflects the fact that in reality opening of windows boosts the ventilation, when temperatures become too high. The programme computes the theoretical requirement of cooling energy to maintain this. The predicted cooling energy is therefore an indicator of thermal comfort.

Diagram 5.1, in Chapter 5, gives an example from project D showing three consecutive days during the summer period. The most critical flat, on the top floor of the building, and facing towards the South, is compared with average values for the entire building. The diagram shows a significant difference with regard to thermal comfort. Over the whole year the theoretical cooling requirement is more than 30% larger for this critical flat compared to the average for the entire building. The explanations are larger solar radiation exposure, in combination with limited thermal mass as walls and the roof structure are of lightweight structures on the top floor. The unlimited possibility to have open windows during nights to allow cross ventilation will probably eliminate this potential problem.

7.5.7 ILCD findings and discussion

The study indicates that the overall performance of the D building is good in comparison with the existing building stock of the housing company. Particularly the energy characteristics are excellent.

There is a risk of contradiction between thermal comfort during summer and low energy requirements. For the sake of energy efficiency, solar gains should be maximally utilised during the heating season. However, in combination with good insulation, and thus low transmission losses this may lead to high indoor temperatures during summer. By an integrated analysis of thermal characteristics, such as U-values and heat capacity, window orientation and solar shading devices optimised with regard to solar altitudes, and ventilation and heating regimes, this conflict can be avoided. The possibility to utilise cool night air to cool down the building structure is particularly interesting.

7.6 Example E

Example E is presented in an internal report for the project team (Öberg, 2004-E).

7.6.1 Background

This case refers to a large multi-dwelling project in a community close to Stockholm, cf. Figure 7.7. This is an own development project undertaken by one of the major Swedish construction companies. The flats are sold directly to the end-user, and the whole building is turned over to a housing cooperative, which is formed for the management of the building. The contractor was interested in the ILCD method, and the researcher was invited to perform a study on this particular project. This building was also used as a reference for the examination of a new type of façade element, c.f. Section 7.7.

Figure 7.7 Example E. Façade. Sketch with permission from the architect: Jan Borek. Grappa, Arkitektur och Form. Stockholm

This is a typical modern Swedish multi-family dwelling building, with a slab block structural frame, cf. Annex 4.A. It has internal walls of 200 mm thick concrete elements and cast in place concrete floors on prefabricated floors-slabs, with a total height of 240 mm. The long side façade is a curtain wall with interior gypsum board, timber studs, mineral wool, and in this case rendering on the outer insulation as outer surface. The building has mechanical exhaust ventilation. Design of thermal insulation and other characteristics influencing energy performance is done according to current Swedish energy performance standard. This permits exception from a general rule of heat recovery from exhaust ventilation, if the energy source uses less than 50% fossil fuels, which is here.

7.6.2 Task

The task was to provide a general whole life evaluation of the building that was under construction.

7.6.3 Method

A quantitative and qualitative analysis was conducted, utilizing relevant parts of the ILCD toolbox. A representative section of the building, comprising a net usable area of 704 m^2 and 12 flats was examined.

7.6.4 Life cycle appraisal of the building

Detailed input data for the calculations are tabled in Annex 7.E and 6.F.

Table 7.12 Predicted life cycle costs for example E compared to average costs for the geographical area, age group and type of tenure. Calculation horizon 60 years

Cost item	Present value	Annual cost	*Average**
	Euro/m^2	Euro/m^2	*Euro/m^2*
Administration	85	2,7	*7,9*
Care-taking	88	2,9	
Water and sewage	88	2,9	
Electricity (common)	65	1,6	
Waste disposal	23	0,5	*5,5*
Heating	294	7,5	*9,3*
Insurance	14	0,4	0,4
Miscellanous	41	1,3	1,6
Periodic maintenance	183	5,9	*8,6*
Sum	880	26	33
Capital costs***	-	-	*25,7*
Property tax		5,4	*4,9*
Total	**-**	**-**	***64,1***

* *Average costs for modern multi-dwelling buildings in the Stockholm area in housing cooperatives. SCB (2001).*

Table 7.13 Predicted energy balance of project E.

Energy losses (kWh/m²,year)					Energy supply (kWh/m²,year)			
Trans-mission	Air leaks**	Ventilation	Hot tap water	Overtemp *	Solar gains	Other free gains	Heat recovery	**Bought energy**
78	-	77	49	21	57	44	-	**123**

** Theoretical requirement of cooling energy when indoor temperatures pass a comfort limit set to +27ºC*

*** This is accounted for in the necessary intake air for ventilation. The true air leaks are thus not visible in the energy balance.*

According to Swedish building regulations the building does not fulfil the requirements according to the U-value approach. The actual mean U-value is 0,32 W/m^2K and the required is 0,31 W/m^2K, cf. Section 4.6. However with the EP – approach the building satisfies the regulations. The calculated energy use for the building is 95 kWh/m^2,year while the reference building consumes 104 kWh/m^2,year. The difference between the EP-approach calculation 95 kWh/m^2,year and the prediction presented in Table 7.13 is primarily due to lower indoor temperature, +20ºC according to the basis for the EP – calculation. The results in Table 7.13 is based on +22ºC, which is in line with the average value presented by indoor climate investigations (Engvall and Norrby, 1992).

The building has better calculated energy performance in comparison with average energy use for heating in new Swedish multi-dwelling buildings, 140 kWh/m^2,year, cf. Section 4.6.

7.6.5 Acoustic properties

The calculations show that the building qualifies for acoustic class B with regard to impact sound pressure and airborne sound insulation through walls between flats. The thickness of concrete is 240 mm in slabs and 200 mm in interior walls. The airborne sound insulation through the floors is somewhat lower and fulfils a level in between B and C, were C is the threshold value for new buildings according to the Swedish building regulations, cf. Diagram 7.2.

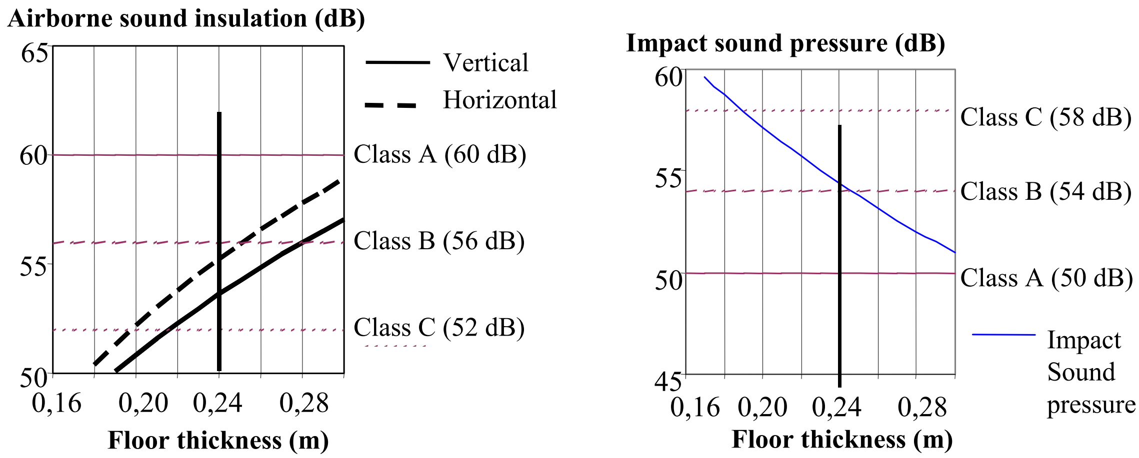


Diagram 7.2 Airborne sound insulation and impact sound pressure for example E with different concrete floor thickness, according to Ljunggren (2000).

7.6.6 ILCD findings and discussion

In the ILCD process, compare Figure 3.3, this example can be referred as part II, life cycle appraisal. The analysis indicates that the energy performance of the building is in line with or for some aspects better than the current practice in new Swedish residential buildings. The sound insulation is also better than the minimum norm-standard.

7.7 Example F

Example F is presented in an internal report for the element producer (Öberg, 2004-F) and by Öberg (2004:2).

7.7.1 Background

A precast concrete element company introduced a new type of façade element. It was of interest to compare this new product with the typical existing façade, from the holistic life cycle perspective. The façade is shown in Figure 7.8.

The façade is a structure of fundamental importance for the performance of a building. The primary lifetime quality factors that were deemed relevant are:

- Mechanical behavior.
- Building physics – acoustics, moisture behavior, thermal insulation and heat capacity.
- Durability - periodic maintenance.
- Environmental burden.
- Life cycle costs: Production, energy, maintenance and insurance costs.

Figure 7.8 Example F-wall. New façade element in finished building. Photo with permission from Skandinaviska Byggelement AB.

The new façade ('FW') is of sandwich type with an inner surface of gypsum board, a special lightweight aggregate inner leave, mineral wool and an external cladding of rendering. The thickness of the concrete and of the insulation layers is variable. The total thickness of the wall is 315-385 mm depending primarily on the thickness of the insulation.

The typical alternative ('Reference') is a lightweight curtain wall with timber or steel joists and insulation of mineral wool, inner surface of gypsum board and outer surface, in this case rendering on thermal insulation, similar to the FW. The total thickness of the reference is 290 mm.

7.7.2 Task

The task was to provide a general whole life evaluation of the FW façade element and compare that with the common reference façade alternative.

7.7.3 Method

Strategic components, such as in this case a façade, interacts with other elements and systems of the building. Therefore, the overall performance of a building needs to be assessed both with the component and with the reference alternative, in order to obtain a relevant comparison.

A quantitative analysis of a typical Swedish residential building with the new element was conducted with the ILCD toolbox and compared with a similar analysis of the reference alternative. The building used as test object was the example E building. Furthermore, a qualitative comparison between FW and the reference was conducted based on the criteria matrix defined in Table 5.2, and was concluded by a comparison based on the MADA methodology.

7.7.4 Life cycle appraisal of the façade

The result of the life cycle cost and energy use calculations conducted with the ILCD toolbox is presented in Table 7.14. (Öberg, 2004-F)

The calculation of heat-transmission for the FW wall alternatives was based on a lambda value for the lightweight aggregate concrete of 0,112 W/m,K. This value was obtained from the element producer (Wäppling, 2004). The U-value for the FW 100 element is thus 0,23 W/m^{2o}C, for FW 125, 0,21 W/m^{2o}C, and for FW 150, 0,19 W/m^{2o}C. The reference curtain wall has the U-value 0,21 W/m^{2o}C.

The FW wall is 25-95 mm thicker than the reference curtain wall depending on insulation. In the thicker wall, FW 150, this effect the life cycle economy as some usable area may be lost. This is the case if the outside perimeter of the building is fixed. For a theoretical case with a flat of 100 m^2 with 10 to 20 m façade the loss is 10 or 20 x 0,095/100, which is equivalent to 1-2% of the floor area. With a rental revenue of 110 Euro/m^2,year the effect on the net present value of 60 years is thus 35-70 Euro/m^2,year. Here, the mean revenue: 52 Euro/m^2,year is used.

Table 7.14 Quantitative life cycle appraisal between reference (typical current type) and new façade element with two different levels of thermal insulation. The relation between wall and floor area is 337/704 = 0,48. Cf. Annex 7.F.

Life cycle cost (Euro)	**Euro,ELU/m^2,wall-area**			
Present value, 60 years	Reference	FW 100	FW 150	FW 150-f*
Production incl. work on site	145	137	141	141
Periodic maintenance	29	19	19	19
Insurance (diff. to reference)	0	-7	-7	-7
Heating (difference to reference)	0	4	-5	-5
Rental loss by fixed perimeter				52
Sum	**174**	**153**	**148**	**200**
Socio economy, 60 years (ELU)	**0**	**5**	**-5**	**-5**
Life cycle cost including socio economy, 60 years	**174**	**158**	**143**	**195**

** Fixed outer perimeter of building*

The difference with regard to energy use, and thus socio-economy, is small. It should be noted that this refers to the total energy use of the building, which is dependent on a lot of other factors such as the ventilation and also other parts of the climate shield; roof, windows etc.. The added thermal mass by the façade is relatively small in relation to the total thermal mass of the building, so transmission and air tightness are the decisive energy factors. Insurance cost must be estimated for the whole building, why only the difference is relevant to include here. The qualitative comparison is concluded in Table 7.15.

Table 7.15 Comparison between FW and reference façade type based on the ILCD criteria matrix in Table 5.2.

Attribute	Comment
Mechanical resistance and stability	FW is stiffer than reference why movements of the façade with regard to wind are smaller.
Safety in case of fire	REI 60 in comparison with EI 30 for reference.
Indoor environment	Inorganic composition of the FW is safer with regard to moisture, in comparison with reference with timber studs and equivalent in case reference with steel studs. Due to better air tightness of FW the risk for cold draughts is smaller than the by the reference.
Safety in use	FW ranks in the highest protection class Sk3 while reference corresponds to Sk1. Normally Sk1 is deemed sufficient for a dwelling building. A higher class enables other applications, which increases the possibilities with regard to adaptability of the FW wall.
Acoustics	Acoustic examination has been undertaken and design guidelines have been developed by the producer. Compared to the lighter curtain wall type the air borne sound insulation for FW with regard to low frequency sound from the outdoor environment is normally better. Should be assessed in the specific case.
Energy use	Heat transmission is equivalent at 125 mm insulation of FW. Air tightness better for FW, particularly in the long-term perspective since the tightness of the reference is dependent of plastic foil. Connections to windows, floors etc. are easy to design and execute airtight.
Durability	Risk for cracks in the rendering is smaller for FW because of its higher stiffness than the reference. The long-term effect of this could be examined on existing buildings.
Robustness and risks	FW is more robust than the reference with regard to stiffness, indoor climate and mechanical damage.
Lifetime usability/ functionality. FlexD	No significant difference
Architecture	No significant difference
Life cycle costs	Compare Table 7.14
Global environment and resource use	Compare socio-economic cost in Table 7.14.

7.7.5 Ranking of alternatives with MADA

The multiple attribute ranking aid MADA, presented in Section 5.6 is applied. The lifetime quality of the façade expressed by Table 7.15, can be presented in the decision tree according to Figure 7.8. Here the assumed relative importance of each attribute is also stated, expressed in %.

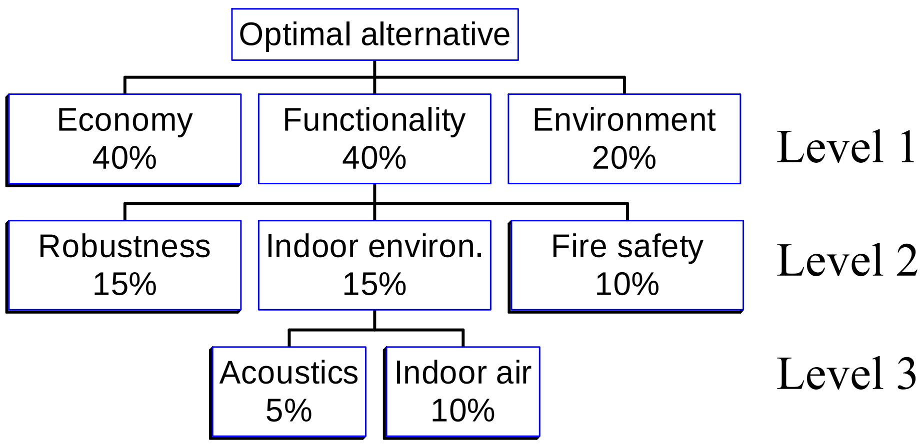


Figure 7.8 Hierarchical tree structure.

The decision matrix is presented in Table 7.16. The resulting MADA ranking of the alternatives is displayed in Table 7.17.

Table 7.16 Decision matrix including predicted performance for the alternatives.

Attribute			Alternative			Unit
Level 1	Level 2	Level 3	Reference	FW 100	FW 150	
Economy. Table 6.14			174	153	148/200*	Euro/m^2, wall-area
Function-ality	Robust-ness		Fair	Very good	Very good	Verbal**
	Indoor environ-ment	Acoustics ****	Fair/ Good	Good	Good	Verbal**
		Air quality	Fair	Fair	Fair.	Verbal**
	Fire safety		EI 30	REI 60	REI 60	Fire class
Environ-ment			0	+5***	-5***	ELU/m^2, wall-area

** 200 with fixed outer perimeter, cf. Table 7.14.*
*** According to Table 5.5.*
**** Of a total of 669 ELU//m^2 that is less than 1% difference.*
***** Fair in noisy ambient such as near city traffic.*

Table 7.17 Final ranking of FW100 and FW 150 walls in relation to the reference.

	Reference	FW 100	FW150	FW150 fixed perimeter
Economy	0,40	0,455	0,470	0,348
Robustness	0,15	0,300	0,300	0,300
Acoustics	0,05/0,075	0,075	0,075	0,075
Air quality	0,10	0,100	0,100	0,100
Fire safety	0,10	0,150	0,150	0,150
Environment	0,20	0,198	0,201	0,201
Sum	**1/1,025**	1,28	1,30	1,17

7.7.6 ILCD findings and discussion

In this example the results indicate that the FW façade is advantageous in comparison with the reference, both from a production and the user phase perspective. Production cost is slightly lower, 3 to 6%, and the maintenance and insurance costs are also slightly lower. With regard to the functional quality, important aspects such as fire safety, robustness and protection against low frequency noise, are advantageous for FW. The FW 100 and FW 150 are in principle equivalent if the perimeter of the building is not fixed. With a fixed perimeter some rent-able area is lost for the thicker FW 150 wall, and the FW 100 is thus preferred.

The ILCD method is very suitable for product development applications such as shown by this example. The criteria scheme according to Table 5.2 is a practical checklist, and the tools for quantitative assessment facilitate comparisons between alternatives. Certain aspects, such as energy performance, acoustics, and in this case insurance cost must be evaluated with the product integrated in the building, as these are performance aspects that are interrelated with other systems and components.

In this case, representing product development, full environmental assessment by LCA is recommended.

7.8 Example G

Example G is presented in an internal report for the client (Öberg, 2004-G) and by Öberg (2004:2).

7.8.1 Background

Example G is furnished by a large semi-public housing company, in the city of Malmö, in Southern Sweden. The project comprises, among other buildings of different types, 7 identical multi-dwelling blocks, cf. Figure 7.9. The researcher was invited to test ILCD, in an early pre-planning phase of this project. The objective was to test how ILCD can be applied in the earliest project phases, and furthermore, to introduce the methodology to this client.

Figure 7.9 Façade of example G. With permission by the architect.

7.8.2 Task

The task was to:

- Compile a set of initial functional, environmental and economical criteria for the building.
- Draft relevant alternatives with regard to structural frame and ventilation system matching the criteria, based on the winning contribution to the architectural contest for the project.
- Arrange components and systems into groups of equivalent service life in order to establish relevant packages for modularisation of the building.
- Predict the lifetime quality of a selected alternative with the relevant ILCD tools.

Note that this example deals with the earliest project phase, were the focus is to outline an initial specification. More detailed design, including development and evaluation of alternative solutions, was not carried out, since the planning of the whole project was suspended.

7.8.3 Method

The drawings for an architectural contest on the project were used as base for the work. A set of criteria was compiled, covering functional aspects as well as a target environmental burden and a target rent, based on information given by the client. Two different structural alternatives were drawn up, one precast and one cast in place on precast floor slabs. In order to obtain good flexibility long spans were targeted for both alternatives.

The ILCD toolbox according to Chapter 5 was applied to predict lifetime performance. Modularisation of the building was done by firstly establishing the theoretical maintenance intervals for strategic systems, according to the maintenance database in the ILCD toolbox. After that the components were clustered into three groups, each with common service interval.

7.8.4 Proposed design criteria

In Table 7.18 a preliminary design brief is compiled following the criteria matrix presented in Table 5.2.

Table 7.18 Initial design brief for project G

Attribute	Comment
Mechanical resistance and stability	Fulfilling requirements of flexibility, below
Safety in case of fire	REI 120
Indoor environment	Indoor environment health and comfort classes B
Safety in use	Protection class Sk 1
Acoustics	Sound class B
Energy use	90 kWh/m^2 Spaceheating, hot water and common electr.
Durability	Optimised according to modular planning. Support: 120 y
Robustness and risks	Maximum robustness with regard to indoor climate
Life time usability/ functionality.	Full flexibility with regard to positioning of walls within flat
Architecture	Referring to the architect proposal, cf, Figure 7.9, a light coloured façade of concrete or rendering is conceived.
Life cycle costs	Rent maximum 120 Euro/m^2, year
Global environment and resource use	According to energy requirement.

7.8.5 Proposed structural designs

Two alternative structural alternatives were outlined according to Figure 7.10.

<u>Alternative A1</u>: Cast in place with or without precast concrete floor slabs. Load-carrying concrete façades and concrete walls separating the flats. This alternative was designed without post-tensioned reinforcement, and the structural capacity was thus fully utilised. The pre-design tool in the ILCD-toolbox is not capable of solving that type of problem. To secure structural capacity and in particular limited deflections, an analysis was performed by a specialist designer.

<u>Alternative A2</u>. Precast concrete with hollow core slabs and sandwich panel façades.

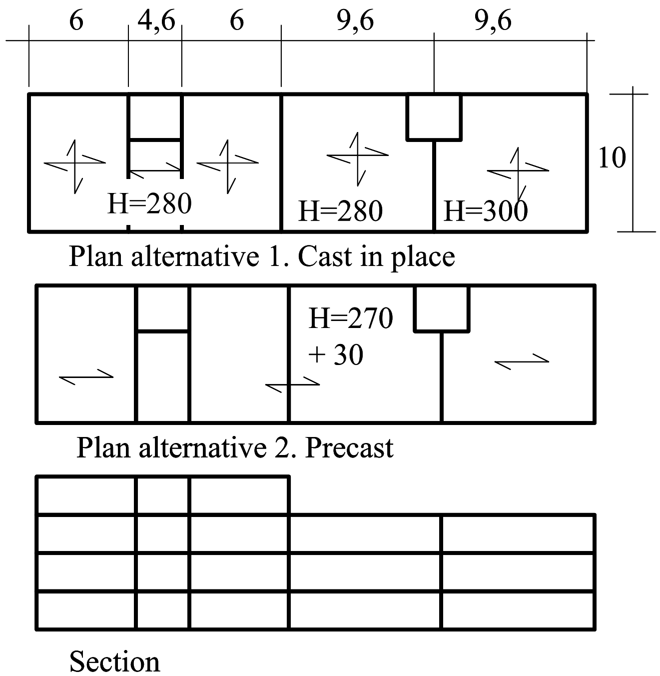


Figure 7.10 Structural alternatives outlined. Arrows indicate load-bearing direction.

7.8.6 Modularisation

In order to cluster strategic components into modules for service life planning the periodic maintenance table was analysed. The table is drawn up using the periodic maintenance module of the LCC tool, described in Section 5.11.

First the strategic components were picked out. In this case all components with an annual maintenance cost exceeding a specified value (here 0,1 Euro/m^2 floor area), calculated as annual cost, were selected, cf. Table 7.19.

The activities were sorted into three groups: 10-20, 20-30 and 30 to 50 years with a target service life selected to match the others, that is at 15, 30 and 45 years. In Table 7.20 the modules for periodic maintenance are presented.

In a real case the maintenance scheme will comprise all planned activities, not only the most costly, as here.

Table 7.19 Periodic maintenance for strategic systems and components.

Component and activity	Interval Years	Number of units or area	Cost per unit Euro	Cost Euro	Annual cost Euro/m^2
Repaint flats	13	17	2835	48198	2,10
Sewage system, replace	45	17	6121	104055	0,78
Windows, replace	35	110	725	79780	0,77
Elevators, replace	30	2	30220	60440	0,66
Repaint stairways	15	2	6967	13934	0,47
Washing machine, replace	12	17	536	9116	0,42
Parquet, polishing	17,5	1200	11	13187	0,41
Parquet, eplace	45	1200	44	52747	0,40
Refr., freezer, replace	13,5	17	519	8827	0,37
Stowe, replace	17,5	17	495	8407	0,25
Ventilation fans, replace	22,5	2	3451	6901	0,24
Roof – sheet steel, replace	42,5	397	77	30538	0,24
Repaint façade	17	954	8	7338	0,23
District heating unit, replace	30	1	18462	18462	0,20
Ventilation inspection	3	1420	1	780	0,18
Kitchen furnish, replace	35	17	791	13451	0,13
Rainwater details, replace	27,5	397	16	6544	0,11
Bath/toilet furnish., replace	32,5	17	654	11115	0,11
Repaint doors	20	85	57	4857	0,11

The packaging of maintenance actions in groups, guides the lifetime optimisation of the building by enabling:

- Planning for rational execution of the service activities. Efficient large work packages can be established and components that belong to different categories, with regard to access for service or exchange, can be physically separated.
- Coordination of target service lives for components and systems. For example, the selection of material durability properties can be done with consideration of the adjoining structures.

The periodic maintenance cost is recalculated with the intervals given by the service life planning scheme for the selected design alternative.

Table 7.20 Scheme for modular service life planning.

Component and activity	Year 15	Year 30	Year 45	Year 60	Year 75
Repaint flats	▲	▲	▲	▲	▲
Sewage system, replace			▲		
Windows, replace		▲		▲	
Elevators, replace		▲		▲	
Repaint stairways	▲	▲	▲	▲	▲
Washing machine, replace	▲	▲	▲	▲	▲
Parquet, polishing	▲	▲	▲	▲	▲
Parquet, replace			▲		
Refr., freezer, replace	▲	▲	▲	▲	▲
Stowe, v	▲	▲	▲	▲	▲
Ventilation fans, replace	▲	▲	▲	▲	▲
Roof - sheet steel, replace			▲		
Repaint façade	▲	▲	▲	▲	▲
Heating unit, replace		▲		▲	
Ventilation inspection	▲	▲	▲	▲	▲
Kitchen furnish, replace		▲		▲	
Rainwater details, replace		▲		▲	
Bath/toilet, replace		▲		▲	
Repaint doors	▲	▲	▲	▲	▲

7.8.7 Results

<u>Structural design</u>

Alternative A1 with non-pretensioned massive concrete slabs needed detailed analysis, which was obtained by calculations with a concrete design computer programme FEM-Design 5.0 (Strusoft, 2002) operated by Noren (2004). Figure 7.11 shows the calculated maximum deflections and the thickness of slabs.

For alternative A2 with prestressed hollow core slabs spanning maximum 9,6 m the 270 mm thick slab could be used according to BE (2001)

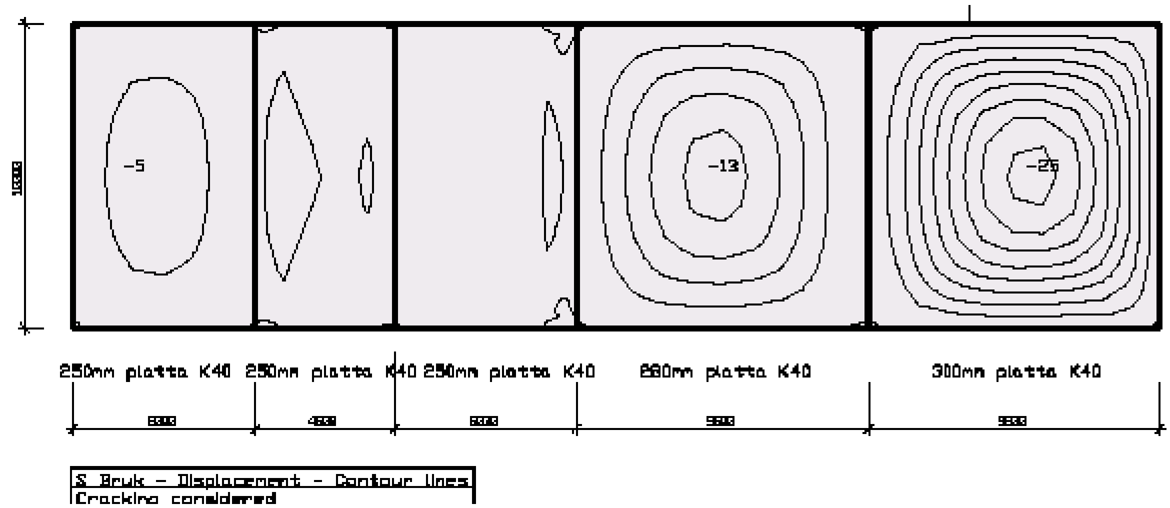


Figure 7.11 Maximum deflections for cast in place alternative. (A1)

The energy use and indoor temperatures were calculated with the VIP+ programme, in the ILCD toolbox. Climate data are from Lund 2001. Lund is situated 30 km from the specific site of the building. The final design concept is shown in Table 7.21 and the resulting energy performance in Table 7.22.

Table 7.21 Energy design concept finally selected.

Component	Type	Area	U-value	Air leakage by 50 Pa
		m^2	$W/m^{2o}C$	m^3/m^2,h
Exterior wall N/E/S/W	Concrete, insulation, concrete or rendering	133/278/ 133/241	0,23	2
Windows N/E/S/W	3-glass	24/83/ 24/124	1,3	3
Entrance door E/W		12/7	1,4	3
Roof	Concrete, insulation	400	0,10	1,5
Slab on ground. Outer	Concrete, insulation	120	0,25	-
Slab on ground. Inner	Concrete, insulation	278	0,19	-
Interior wall	Concrete	438		
Interior wall	Light	525		
Interior floors	Concrete	1023		
Design temperature winter: +22ºC. Free gains from persons and appliances: 5 W/m^2				
Ventilation: 0,35 $l/s,m^2$. Heat recovery on exhaust ventilation air: 60% efficiency. Intake air minimum +20. During summer no heat recovery minimum air temperature.				
Wind conditions: Open				
Windows glass area: 80%, transmittance 70%				

The two design alternatives A1 and A2 are deemed equivalent with regard to energy performance, since they are conceived with identical thermal insulation, and, furthermore, have very small differences in thermal capacity. An alternative with simple mechanical exhaust ventilation was initially considered but was rejected because of the high ambition with regard to energy performance, which made heat recovery on exhaust air necessary. Also experience on the quality of indoor climate lead to this choice, cf. Annex 4.A, Diagram 4.A.2.

Table 7.22 Results from energy balance calculation.

Energy losses (kWh/m^2,year)					Energy supply (kWh/m^2,year)			
Trans-mission	Air leaks	Ventilation	Hot tap water	Overtemp *	Solar gains	Other free gains	Heat recovery	**Bought energy**
68	10	63	39	28	65	32	44	**69**

** Theoretical requirement of cooling energy when indoor temperatures pass a comfort level.*

The common electricity should be added to the energy consumed for heating and tap water. Erlandsson 2004 estimates common electricity 16 kWh/m^2 for multi-dwelling buildings according to different statistical sources. Thus the total predicted energy requirement; 85 kWh/m^2,year, is lower than the brief 90 kWh/m^2,year, in Table 7.18, with some margin.

Acoustic design was done with the simplified tool included in the toolbox. Airborne sound insulation was decisive in this case. Class B according to the design objective could be reached with a 280 mm concrete slab, cf. Diagram 7.3. According to the programme, the thickness of the separating wall should be 40 mm less than the slab thickness, to obtain the result displayed in the diagram.

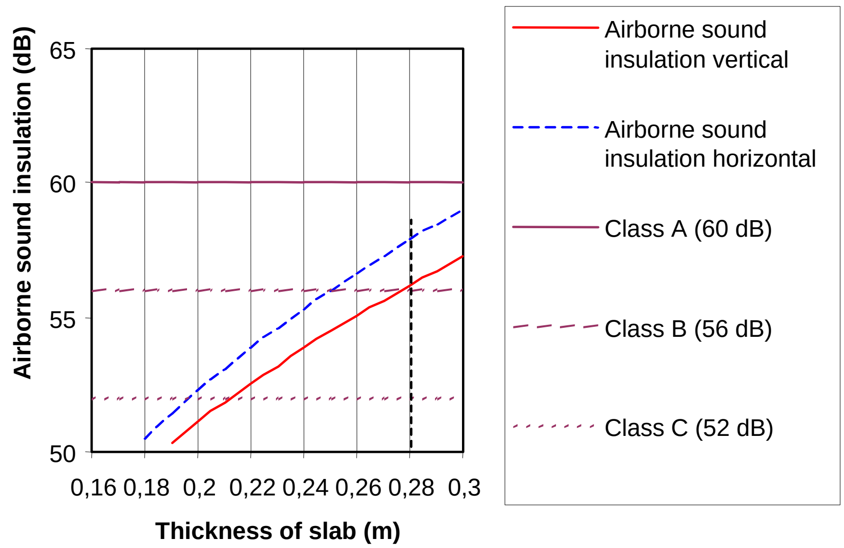


Diagram 7.3 Airborne sound insulation for example G with different concrete floor thickness, according to Ljunggren (2000).

The project economy was assessed by computing life cycle costs with LCC module in the ILCD toolbox, with input from the energy balance calculation and periodic maintenance according to the modular service scheme in Table 7.20. The results are presented in Table 7.23.

Table 7.23 Predicted life cycle costs for example G, alternative A.2, compared to average costs for the entire building stock of the client.

Cost item	Present value	Annual cost	*Average**
	Euro/m^2	Euro/m^2	*Euro/m^2*
Administration	195	6	*7*
Caretaking	256	8	*8*
Water and sewage	120	4	*3*
Electricity (common)	76	2	*3*
Waste disposal	51	1	*2*
Heating	211	5	*10*
Insurance	20	1	
Miscellanous	76	2	*1*
Periodic maintenance	380	12	*13*
Sum	1385	42	*46*
Capital costs**	-	-	*22*
Property tax	125	5	*4*
Total	**-**	**-**	***72***

** Average costs for total stock of the housing company during 2003*
*** Calculated as: Interest 8,8 – Subsidies 0,5 + depreciation 13,5 Euro/m^2 during 2003. Capital costs for the project can be estimated by the client based on the financing possibilities at hand..*

The two structural alternatives A1 and A2 are equivalent with regard to operating costs except for maintenance of the façade surface. The differences have limited impact on the overall lifetime costs, cf. Table 7.19, and should be further assessed at a later stage of the project. In Table 7.23 the periodic maintenance cost is based on the A2 concept with concrete sandwich facades.

The objective was a maximum rent of 120 Euro/m^2,year, according to the brief, presented in Table 7.15. This implies that after operating costs of 42 Euro/$m^2$and property tax 5 Euro/m^2, there is 73 Euro/m^2,year left to cover capital costs and provide revenues on this project.

7.8.8 ILCD findings and discussion

This example illustrates the use of ILCD from the very early project phase for investment planning based on the first architectural sketches. Analysis of the client needs and establishing functional specifications led to the design brief that covers requirements for strategic aspects. From that, technical specifications on the building were elaborated, including two different structural solutions. Finally a modular life cycle planning was outlined.

The project economy is clarified, relating to the defined lifetime quality levels. With this information the client can decide if the project can be continued based on the initial brief or if modifications are required.

7.9 Example H

Example H is presented in an internal report for the client (Öberg, 2004-H).

7.9.1 Background.

The H-project was in the investment planning phase when the researcher was invited join the project team to apply the ILCD toolbox. The project group consisted of the client, a semi-public housing company, the architect and a construction management consultant. The objective was to construct 16 small flats, in a two-storey building having good energy performance and fairly low rents. Architectural drawings are displayed in Figure 7.12.

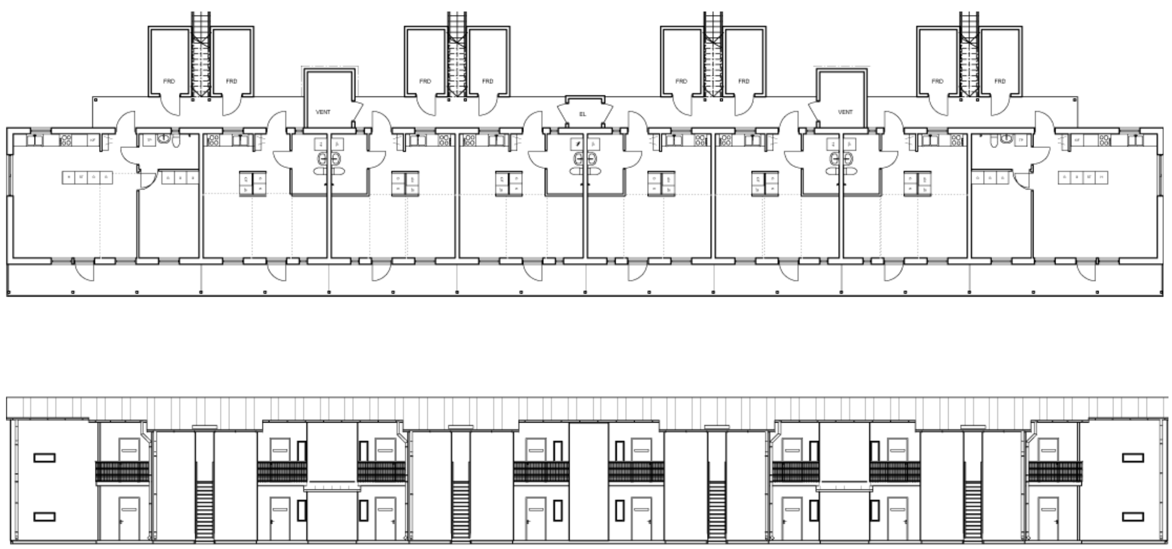


Figure 7.12 Example H. Plan and façade. With permission from Arcum Arkitektkontor. Uppsala

7.9.2 Task

The task was to study the life cycle consequences of a low energy strategy in comparison with current practice level, as a part of the general pre-design procedure to establish if the project would be economically feasible.

7.9.3 Methods

The architect had drafted an outline of the building including the structural frame. The design concept is one single, long, two-storey, balcony access building with a slab block concrete frame, cf Annex 4.A, and a curtain wall façade, with fiber-cement board as surface material. The construction management consultant was engaged by the client to advice on alternative solutions, and to estimate building costs for the different alternatives, that were considered.

Three different energy concepts were conceived by the project group, cf. Table 7.24: ‘LE’: Low energy, ‘NEX’: Norm energy, supply and exhaust ventilation with heat recovery and ‘NEF’: Norm energy with mechanical exhaust ventilation with demand controlled operation. The low energy alternative was designed with thermal insulation, representing the current best available Swedish practise. Calculation data are further presented in Annex 7.G.

Table 7.24 Alternative energy designs for project H.

	U-value ($W/m^{2o}C$)			Ventilation
	Wall	Roof	Window	
LE	0,13	0,10	1.0	Supply and exhaust with heat recovery 80%, 0,5 air changes/hour
NEX	0,22	0,12	1,4	
NEF	0,22	0,12	1,4	Mechanical exhaust ventilation Low flow: 08.00-16.00: 0,1 air changes /hour High flow: Other times: 0,5 air changes /hour

The ILCD toolkit was used to determine the difference in life cycle cost and environmental performance as well as the total life cycle cost. Finally the ranking instrument, MADA, was applied to determine the most suitable alternative according to a specific priority.

7.9.4 Results

The alternatives differ with regard to building cost, heating cost, cost for periodic maintenance, environmental burden and indoor climate. Tables 7.25 and 7.26 show periodic maintenance and energy balance, respectively. Table 7.27 shows a summary of the results of the quantified life cycle appraisal. Table 7.28 presents the total life cycle cost results.

Table 7.25 Predicted periodic maintenance (Present value Euro/60 years).

Action	Number	Cost Euro	Cost total Euro	Interval Years	Present value Euro
LE and NEX					
Supply and exhaust vent exchange	2	2824	5648	20	5549
Exhaust fan	2	3451	6901	22,5	6231
Intake fan	2	2462	4923	22,5	4440
Exchange out-and inlet	64	37	2391	22,5	2198
NEF					
Exhaust fan	2	3451	6901	22,5	6231
Exchange outlet	32	37	1196	22,5	1099

Table 7.26 Predicted energy balance of alternative designs of project H

	Energy losses (kWh/m^2,year)					Energy supply (kWh/m^2,year)			
Alternative	Trans-mission	Air leaks	Ventilation	Hot tap water	Overtemp *	Solar gains	Other free gains	Heat recovery	**Bought energy**
LE	72	12	65	62	22	49	44	41	**99**
NEX	91	12	64	62	23	56	44	41	**113**
NEF	91	3	41	62	24	56	44	0	**126**

** Theoretical cooling energy needed to maintain indoor temperatures < +28° C*

Table 7.27 Quantitative life cycle appraisal. Difference to LE alternative

Life cycle cost. Present value, 60 years (Euro/m^2)	LE	NEX	NEF
Project cost	0	-55	-115
Periodic maintenance	0	0	-18
Heating	0	35	67
Sum	**0**	**-20**	**-66**
Socio-economic cost 60 years (ELU/m^2)	**0**	**40**	**78**
Life cycle cost including socio-economy (Euro/m^2)	**0**	**-9**	**12**

Table 7.28 Predicted life cycle costs for example H, LE –alternative and average costs for the entire building stock of the client.

Cost item	Present value	Annual cost	*Average*
	Euro/m^2	Euro/m^2	*Euro/m^2*
Administration	194	6	*12*
Caretaking	217	7	
Water and sewage	186	5	*7*
Electricity (common)	65	2	
Waste disposal	47	2	
Heating	262	7	*11*
Insurance	17	1	*6*
Miscellanous	65	2	
Periodic maintenance	472	15	*13*
Sum	1525	46	*49*
Production cost	2000		
Capital costs***			*35*
Property tax	106	4	*3*
Total	3600	-	***87***

7.9.5 Ranking of alternatives with MADA

The multiple attribute ranking aid MADA, presented in Section 5.6 is applied to aid the selection of design alternative. The aspects in Figure 7.12 are taken into account in the comparison. Other aspects are deemed to be equivalent. Here the relative importance of each attribute, as defined by the author, is also stated, expressed in %.

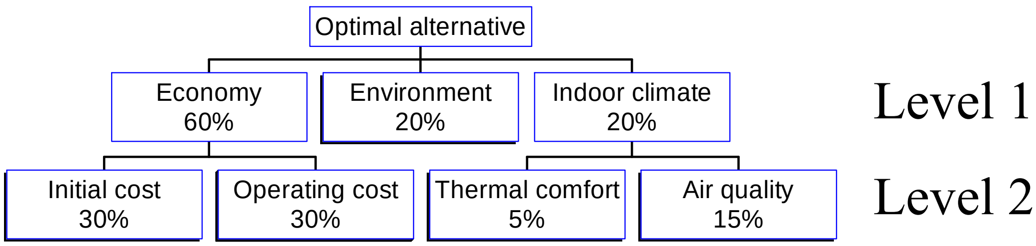


Figure 7.12 MADA decision tree

The decision matrix is presented in Table 7.29 and the resulting MADA ranking of the alternatives is displayed in Table 7.30.

Table 7.29 Decision matrix including predicted performance for the alternatives.

Attribut		Alternative			Unit
Level 1	Level 2	LE	NEX	NEF	
Economy	Initial cost	2000	1945	1885	Euro/m^2
	Operating cost	1525	1560	1574	
Indoor climate	Thermal comfort	22	23	24	Overtemp. Cf. Table 7.26
	Air quality	B	B	C	ICC Class. Cf. Section 4.3
Environ-ment		338	378	416	ELU/m^2

Table 7.30 Final ranking of alternatives

	LE	NEX	NEF
Initial cost	0,3	0,308	0,318
Operating cost	0,3	0,293	0,291
Thermal comfort	0,05	0,048	0,046
Air quality	0,15	0,150	0,075
Environment	0,2	0,179	0,163
Sum	1	0,98	0,89

7.9.6 ILCD findings and discussion

This case represents a typical investment planning situation. By the time of writing, the predicted total cost of the project was too high, implying that it had been discontinued. The relatively high building cost of the project is primarily explained by the small size of flats. Each small flat requires the same set of relatively expensive kitchen and bathroom utilities as a large flat, whereby the cost is distributed on a larger area.

To some extent, the operating costs for a small flat suffer from the same condition. For instance energy use for hot tap water is in realty, as well as in calculation programmes governed by an average need per flat plus an additional requirement per m^2. In this case 62 kWh/m^2, year compared to for example A with 32 kWh/m^2. The calculation formula for annual hot water consumption is 1800 kWh + 18 kWh/m^2. It is probable that this an over estimation for a building with a large proportion of small flats, such as in this case. The predicted energy cost for example H is almost on the same level as the total stock of the client, even though the energy performance of the building shell is designed according to best current practice.

With regard strictly to life cycle costs the NEF alternative is preferred with the other norm alternative NEX comes in the second place. From the environmental point of view the order is the opposite. If environment and economy are added the differences are in principle insignificant with approximately 10 Euro, in comparison with the total life cycle cost of 3000 Euro/m^2. Finally, if functional aspects are included, cf. Table 7.30, the two alternatives LE and NEX are equivalent, and superior to NEF.

The way of calculating production costs in this case was discussed. The additional material and working costs for improved energy performance such as increased insulation and low energy instead of normal windows, were multiplied with a rather large costing supplement of 40%. In a real tendering situation it is questioned if, for instance, the change from a less expensive to a more expensive window, or increased insulation, need to carry such large extra general fees.

7.10 Survey on current practice with regard to life cycle aspects

To examine the interest for ILCD and the related issues, a limited qualitative survey was carried out among key persons involved in the application projects. The questionnaire is displayed in Annex 8.A, and the results are reported in Section 8.1.

7.11 Conclusion from the application examples

The pilot ILCD toolbox was easy to use. Approximately five working days were required to analyse a medium sized multi-dwelling building project, based on the construction documents available. The analysis covered a limited number of technical alternatives, which were examined quantitatively and in some examples qualitatively. Note that the QFD-step to analyse the needs of the client was not applied in any of the cases. Many of the projects were already at a late design stage or already built, so the design options were limited. The examples included entire buildings, alternatives with regard to certain parts or systems of a building, and also one case that can be referred to as product development.

The MADA method is a good way to systemise the requirements, utilising the decision tree structure and the decision matrix. The final weighting step is however sensitive and further experience of the method is required. It is envisaged that a repeat order client or a developer of type building concepts may customise the weighting procedure according their specific priorities.

The total life cycle costs for the alternative structural and technical designs in the test projects in Chapter 7, as well as by the theoretical example in Chapter 6, indicated relatively small differences. This can be explained by the fact that in the context of the whole building, the impact of varying only the structure (structural frame and façade) and ventilation systems is limited. For example, the production cost of a structural frame represented 10 to 20% of the total project cost, according to Table 4.7. Since approximately half the life cycle cost refers to the production, a 10% change in production cost of the building frame, represents 0,5 to 1% change of the life cycle cost.

The difference between alternatives with regard to environmental burden over the life-cycle, as quantified with the ILCD tool, was in many cases significant. One recurring question is how the client can benefit from an environmentally superior alternative, except for the direct savings in terms of for instance heating costs.

When the LCC comparison indicates relatively small differences between design alternatives, their functional quality can govern the decision. This is an important conclusion, which should favour the better performance alternatives.

8 INTRODUCTION OF INTEGRATED LIFE CYCLE DESIGN – POSSIBILITIES AND BARRIERS

This chapter discusses how ILCD can be introduced in the design practice both from a principal and practical point of view.

8.1 ILCD - drivers and barriers

8.1.1 ILCD and the need for a total lifetime oriented building practice

The overall importance of the quality of the built environment as the framework for human activity is significant. The impact of the construction and above all operation of buildings, regarding economy and environment in our society is acknowledged. With this background a holistic life cycle perspective should be applied and respected by the design and procurement of buildings. This is encompassed by the definition of sustainable development, cf. Section 2.1.

ILCD is an instrument that directly supports sustainable development by addressing function, economy and environment in a holistic way. This should be a powerful motivator for actors with long-term perspective.

For a client with long-term interest in a project, lifetime performance and economy are crucial, and ILCD is therefore a logical approach. For other actors in the construction process ILCD can be utilised by the development of components, systems and end product – the building – to respond to the need of lifetime quality, for the client and society.

The added value of holistic life cycle considerations for society, industry and client is shown by the application examples in this work. This is furthermore witnessed on by large number of studies such as BKD (2000), which stated that: 'projects should be procured on life cycle costs rather than production costs'. The specific objectives in a project may, however, not always converge from the client, producer and society, as the following examples indicate:

- Benefits that will appear a long time ahead may be found less valuable than short-term advantages. In some cases a project would not be realized if a critical initial cost threshold was exceeded. The client may accept an inferior lifetime solution in order to be able to go ahead with a project. If this decision is taken in full awareness of the future consequences it is hard to refute.
- The incentive to select a 'green' alternative is not always valid from the client position. The question of what in fact is a green alternative can furthermore not always be clearly and definitely answered. However, according to the 'polluter pays principle' the costs on commodities with

environmental burdens increases, by taxes and restrictions in availability. The views of the client and society will therefore step-by-step converge.

These sometime conflicting interests do, however, in no way diminish the value of ILCD. On the contrary, clear, robust and practical methods to predict, assess and compare the lifetime performance of different design alternatives in a holistic way are needed irrespective of the objectives defined for the specific project.

In several application examples agreement could be found between functional aspects, economy and environment. ILCD provides a possibility to find such optimal design alternatives.

8.1.2 Experience from the application examples in Chapter 7

Eight test applications of the ILCD toolbox were undertaken in collaboration with people involved in the projects. All parts of ILCD according to Figure 3.3 were tested, however not all on each specific project.

The arrangement of design criteria, collection of input data, operation of the quantitative tools included in the toolbox, and finally the compilation of a standardised project report, could be done in approximately 5 working days for a medium sized multi-dwelling building project. This implies that the method is operational.

Clients appreciated the MADA tool as a systematic way of organising criteria and comparing alternatives. The method is, however, sensitive with regard to the digitalisation of the different performance indicators, and it must be carefully interpreted. Note that ILCD also can be performed without the weighting of attributes according to MADA.

The trial projects that were undertaken involved different clients and other actors in the Swedish house-building sector. The collaboration with the design teams by introduction of the ILCD principles and toolkit gave a possibility to examine their attitude to holistic lifetime design. To systemise the information, personal interviews were conducted based on a standardised questionnaire, cf. Annex 8.A. It is acknowledged that the results are not representative for the Swedish residential building sector. The number of respondents is far too small and, furthermore, the fact that they are involved in the study biases the answers. However, in spite of this, it was deemed interesting to collect and present their views. In Annex 8.A the questions are listed and the answers are compiled. From the answers the following common opinions are gathered:

Important aspects on residential buildings. Question 1
- The owner prioritises robust structures with good operating economy.
- The tenant prioritises location, low rent, technical standard and good indoor environment.

Long term versus short term objectives. Questions 2-4
- There is not necessarily a contradiction between long- and short term objectives.
- The client's knowledge and consciousness of, and attitude to, lifetime quality issues, is crucial.
- New forms of collaboration between client and the producers are necessary.
- Flexibility and adaptability were not rated particularly important.

The process. Questions 5-6
-Feed back is often neglected, and it is agreed that this item should be improved.
-The client has the largest influence on design decisions. In case the major contracting companies are involved, they also have a substantial impact.

Global environment and resources. Questions 7-8
- The value of good environmental performance for the client is unclear.
- Environment is interesting, but the economical aspect is still more important.

Introduction of life cycle thinking. Question 9
- Both development of methods and change in thinking are needed.
- There is a value on the market for life cycle methodology.

8.1.3 Obstacles for ILCD

Referring to many studies, for instance, Sterner (2002) and BKD (2000), there are some recurring circumstances that hinder the life cycle approach and thus ILCD.

i. The fragmented organisation of the construction sector does not favour the long-term objectives in projects. The important aspect of feedback is also impeded by this fragmented organisation.
ii. The designer and/or producer may lack understanding or knowledge about the user phase.
iii. The design specialists of structure, heating, ventilation, acoustics and other fields optimise their specific part instead of collaborating for the most effective overall solutions.

Fragmentation of the building process may lead to production optimisation of the building, or even worse, of individual components or systems. Then ILCD is redundant.

The complexity of building design, calls for many different fields of expertise already from initial project phases to obtain the necessary holistic perspective. An example of this is the Dutch initiative referred to, in the end of Section 2.2, whereby the different specialists are engaged already at the conceptual phase. Ryding (1995) also underlines the importance of early mobilisation of knowledge, as mentioned in the same section. This is not customary in the typical Swedish multi-dwelling project, and may require some rethinking of the design process. It is acknowledged that design costs would increase if all experts would be engaged from the initial phases, but the potential improvement of the end product is interesting.

ILCD, in general and in particular when it is introduced for the first time, requires an increased effort in design and planning work. This represents an extra investment in design, which is an obstacle that can only be overcome if the client considers that the potential improvement, in lifetime quality and cost effectiveness, is worth it.

ILCD models reported in Chapter 2, and included tools, such as LCA, are often very comprehensive and applied in great detail, which may deter practitioners.

8.2 Introduction of ILCD methodology in the design process

8.2.1 Principles for ILCD introduction

In Table 8.1 the ILCD steps discussed in chapters 3 and 5 are repeated. There is no contradiction between the two columns. The sequence to the right indicates the ILCD specific steps, while Sarja (2002) also includes the traditional design procedures. The table also gives reference to pertinent application examples in Chapter 7. In the desktop study presented in Chapter 6, all steps are performed except for the last, feed back, which cannot be undertaken before the building have been constructed and used for some time.

Steps number 1 to 5 in Table 8.1 cover the critical task to analyse the needs of the client and transfer them to a specification. These steps thus define the relevant functional design criteria. This type of analysis is done also by traditional design, however, more or less systematically. A criteria matrix as proposed in Table 5.2 is the core tool to organize this work. The QFD method proposed in Section 2.6.1 can be applied here to guide prioritisation between different requirements.

As soon as the first sketches are drawn up, the core instrument of the ILCD procedure, as well as any efficient design process, should be mobilised. This is a master 3-D geometrical model of the building. In former times the full model existed only in the head of the designer, while in contemporary design, it is stored in a computer. The model needs to be extended with the time dimension both with regard to life cycle appraisal and production planning. This model should follow the project, with increased level of detail, from the earliest planning phases over detailed design, production, facility management and refurbishment all the way to demolition, recycling and final disposal. Further to the geometry, and thus to the quantities, sets of data on materials and components are needed to facilitate the different kinds of calculation. Preferably all specialists can utilize the same geometric model applying the specific data needed for their share of the work.

Table 8.1 ILCD process steps

ILCD process. Sarja (2002)	*ILCD cornerstones. See Figure 3.*	*Example*
1. Investment planning 2. Analysis of client's and users needs 3. Functional specifications of the building	I. Analysis of client needs. Short- and long-term needs are systematically defined, analysed and prioritised.	G, H
4. Technical performance specifications of the building 5. Creation and outlining of alternative structural solutions		C,F,G
6. Modular life cycle planning and service life optimisation of each alternative	II. Life cycle appraisal. Economical and environmental life cycle appraisal to quantify life cycle consequences of alternative designs	A, B, C, E, F, G, H
7. Multiple criteria ranking and selection between alternative solutions and products	III. Ranking methods. Multiple Attribute Decision Analyses is employed to aid the choice of design with regard to several different aspects.	C, F, H
8. Detailed design of the selected solution		
	IV. Feed back. Information from production and facilities management of the building is systematically recycled to the design team and management	B and Section 5.15.2

Step number 6, life cycle appraisal, requires geometry of the building, quantities and identification of the components, and materials selected. Life cycle data for materials and components that are required are costs, maintenance requirements and intervals including their costs and life expectancy. If a full environmental evaluation with LCA methods is conducted the data should be supplemented with environmental burdens including energy consumption for production, transports, building site, operation including maintenance and end of life cycle.

Step 7, ranking of alternatives, is a stand-alone activity that can be undertaken by the application of multi variable decision analysis as presented with the example in Section 5.14, or with simpler ranking criteria as listed in Section 3.3.7.

Step 8 refines the selected structure within the 3-D model in level of detail, and adds other information needed for the production.

Cornerstone IV closes the circuit by updating the data used by design with information from production and operation phase. Since long, the difficulties to secure and report useful feedback are acknowledged within the building sector.

The concept of using the same core data as discussed above, however, supports feedback by clearly establishing the format, structure and contents of the relevant information.

8.2.2 Practical introduction of ILCD

There are some ILCD tools and activities described above that are of stand-alone character, while most are tightly connected to the regular design process with regard to methods and data. In Chapter 5 a simplified ILCD toolbox was compiled based on existing methods and available data. This can be further developed to rationalise and elaborate the treatment of data to fit the need of a specific client. It is, however, already operative, as shown by the application examples in Chapter 7.

The information could be gathered and retrieved on a collective basis, or managed within a company or organisation. Standardisation of this type of data, such as environmental product declarations, service life planning, lifecycle costing, and improvement of data interchange standards, should further facilitate ILCD.

For successful introduction of ILCD in practice, it is crucial to start with a moderate ambition with regard to detail. Figure 8.1 summarizes how different cost and environmental burdens are dependent on the design of the building. Furthermore, the influence on total life cycle cost or environmental burden, by each category is illustrated, referring to Diagram 4.7 and Adalberth (2000). Water/sewage and waste disposal were not included in the study by Adalberth so their horizontal position is tentative. The conclusion is that production, periodic maintenance and energy are the most critical aspects to assess, when comparing alternatives at an early design phase.

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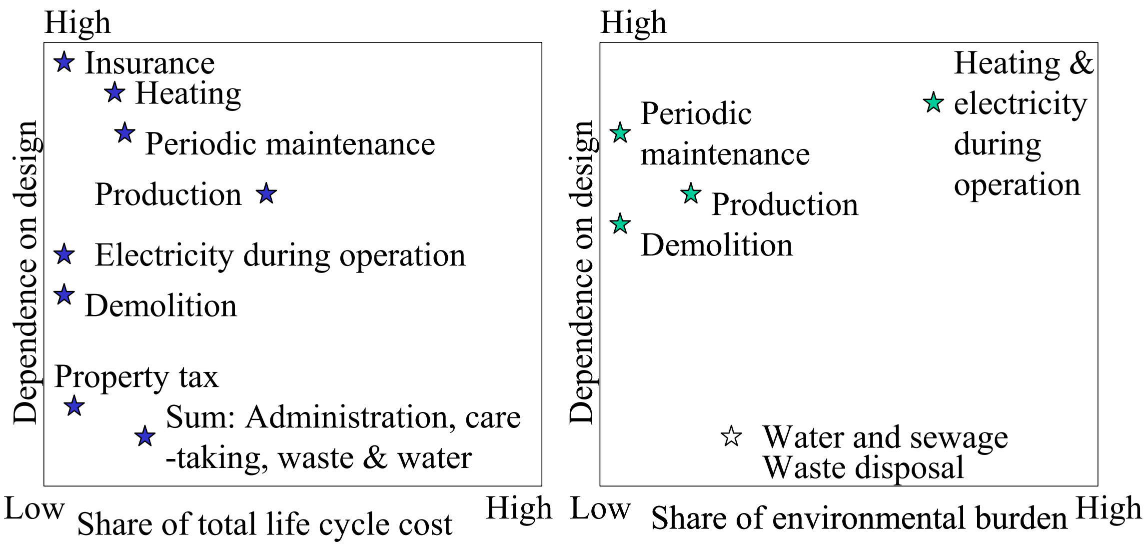

Figure 8.8.1 Distribution of life cycle costs and environmental burden for a Swedish multi-dwelling building and the specific dependence on the design for each item. Data referring to present value of life cycle costs according to Section 4.11 and for share of environmental burden, Adalberth (2000).

By concentrating on the critical aspects for the specific application, the model becomes simple, clear and comprehensible. If, for instance, the task is to rank design alternatives for a normal residential project, the analysis can be limited to:

- Functional performance of a limited number of key aspects. The criteria matrix in Table 5.2 can be used as base.
- Energy balance calculations.
- LCC comprising production cost, energy use and periodic maintenance. Other costs are either small or not dependent on the design.
- Environmental performance based on energy balance calculations and expressed as a socio-economic cost that can be directly added to the LCC.

If the functional performance of the alternatives is equivalent, the quantitative analysis regarding economy and environment, is decisive. Otherwise the functional differences must be evaluated, which can be done with or without the decision aid included in the ILCD toolbox.

If the task is to establish the complete LCC, for example by investment planning, other operating costs are easily added with generic data in the LCC module or specific data for the client.

If the task is to support development of a building concept, or a general specification for a repeat order client, the level of detail can be further increased and include QFD, LCA and MADA.

9 DISCUSSION, FUTURE WORK AND CONCLUSIONS

9.1 Discussion

The essence of ILCD is to address and combine two important perspectives:

1. Life cycle. Meaning that the cost and environmental burden of the building is considered for its entire life. By clarifying the consequences of the alternatives, available to the client, the lifetime quality can be enhanced.
2. Integrated. Implying that the different fields of expertise involved in the design process are combined in a holistic way. Interactions are considered and the properties of building are optimised with regard to the long-term needs of the client.

ILCD can therefore contribute to resolve dilemmas related to the current fragmented building process, often working with time perspectives that are not in line with the life span of the product.

ILCD consists of a combination of traditional design tools, tools for life cycle appraisal, and methods for multiple criteria decision-making. The tools are supplemented with relevant data, and with design criteria. The ILCD toolbox can be used in different levels of detail depending on the specific stage in the design process and the type of application. An important design principle is modularisation, whereby components and systems are classified and optimised according to the target service life.

The potential for improvement of lifetime quality of buildings, by the application of ILCD, is substantial according to other studies, and is confirmed by this work.

Life cycle appraisal with regard to both economy and environment appear to be less accepted in the house-building sector than in, for instance, the manufacturing industry, but also compared to civil engineering. There are several more or less valid excuses for this. However, the potential benefit for the client as well as for society, referring to the large social and environmental impact of the build environment, is large enough to motivate the introduction of life cycle appraisal.

The simplified pilot ILCD toolbox developed in this project can be applied in ordinary design work, and provides a platform for further development. The administration of models and data can be organised in different ways. Larger repeat order clients, consulting companies, construction firms or organisations specialised in the supply of data to the sector, could develop and market parts of or a whole ILCD toolbox.

The few examples studied in this work indicate the importance of adaptability of the building after the specific project conditions and priorities of the client. For example the optimal energy and indoor climate design in Northern Sweden will result in different technical solutions than in the similar building in South Sweden. The energy performance requirements differ as much between Kiruna in Northern Sweden and Malmö in the South, as between Malmö and the south of France, cf. Annex 5.H. It is obvious that optimization for energy economy and thermal comfort must take that into account. Other ambient building physical aspects such as humidity, rain, wind and noise also provide varying demands on the building.

It is acknowledged that rationalisation of the building process implies streamlining and standardisation of processes, technical solutions and systems. Increased emphasis on development of robust, high quality standard solutions is important, and ILCD is a practical tool for this.

Sustainable construction is agile and adaptable to the specific ambient and the client needs. The development and design is governed by the lifetime quality of the building, which is facilitated and safeguarded by ILCD.

9.2 FUTURE WORK

9.2.1 ILCD in the shorter perspective – shortcomings and possibilities

The simplified ILCD tool outlined in this work could be further developed to facilitate the administration of data and links between calculation tools. A logical progression is to include the quantitative life cycle appraisal tools: LCC, energy balance, environmental burden and acoustics in a multi-dimensional product model. Production costs data should be improved. Data for periodic maintenance of different materials and systems could be expanded and refined. Follow up of the predicted performance with regard to the design objectives on real projects, over time, is required for verification and further improvement of data, tools and design criteria.

Multiple attribute decision making, (MADA), should be further examined, developed and tried out in practical building project applications.

Quality Function Deployment (QFD), which has been discussed, but not put into practise, in this work, should be tested in collaboration with a client or producer, as a method to analyse and synthesize the requirements on the building.

The design criteria related to global environment are often not taken seriously into account in practise today. Energy prices are still relatively low and there is little or no benefit for the client from environmental advantages. The relation between economical and environmental (socio-economic) cost should therefore be further clarified and agreed.

Criteria with regard to the indoor climate need to be communicated and applied in practise in order to get general acceptance and to establish their relevance.

Environmental book keeping is linked to economy by socio-economic assessment of the environmental burden. The relationship should be regarded only as indicative. The following aspects need further clarification:

- General agreement on the valuation of different environmental impacts.
- The risk that environmental burden, or a part thereof, is accounted for twice as the cost of, for instance on energy or waste treatment may include an environmental tax.
- The range of environmental stressor taken into account in this work is restricted, implying that the environmental burden is underestimated.

Further parameter studies on different technical solutions with regard to building frame, climate shell and ventilation system should be done to examine how cost effective and robust technical solutions for low energy housing can be obtained.

9.2.2 ILCD in the longer perspective

Further ahead the design model should be connected to production planning including ordering, manufacturing, logistics etc.. It is of particular interest to open a link to facility management. This would greatly expand the use and benefit of ILCD, and is a logical step towards lifetime engineering, compare Section 3.1.

The design programmes and the geometrical model must be supported with data of improved quality. A vision is the access to a general database for materials and components covering all required lifetime, as well as traditional, design information. The following parameters are required:

- Production costs.
- Environmental burdens of production.
- Mechanical and building physical design data.
- Total expected length of service life.
- Maintenance intervals by relevant exposure conditions.
- Maintenance and care-taking activities including costs.
- Environmental burdens of the user phase.
- Information on disposal of the product at end of the life cycle

The database should be continuously updated with feedback of experience from production and use.

Further development and introduction of the combined qualitative and quantitative or self-learning performance indicator models dealing with the building physical performance and robustness are needed.

Design criteria relating to lifetime usability, flexibility and obsolescence of dwelling buildings should be further examined. Its importance is underlined in theoretical work, but received little attention by the persons interviewed in the application projects, cf. Annex 8.A.

9.2.3 Development of buildings with the aid of ILCD

A demonstration multi-dwelling building could be designed and constructed, in principle following the desktop example presented in Chapter 6. The requirements of the client should be analysed, possibly with the aid of QFD. The model set of design criteria presented in Table 5.2 could thus be updated, if necessary. Alternatives with different functional quality levels, relating to the design criteria could be outlined. The consequences with regard to production and operating costs as well as environmental burden should be estimated. The alternative best suited according to the priorities of the client should be selected, based on the MADA method. Finally the project could be followed up by construction and use applying and improving the methods for feed-back outlined in this work.

Looking at the multi-dwelling building of the future, critical questions are:

- How to reduce the energy consumption in the operational phase, without compromising the indoor climate.
- How to reduce the risk for obsolescence and thereby waste of resources. Aspects such as flexibility and adaptability in use, are then of particular interest.

Concrete is a natural ingredient in the multi-dwelling building of the future, however, in logical combinations with other materials. By applying the modular design approach outlined in Section 3.3.6, the optimal combination of materials and systems can be clarified.

The *Open Building* concept discussed in Section 3.3.6 is a modular, systematic approach to organise and design the building, which fits well with the objectives of lifetime engineering. Open Building combines rational, standardised production with high customisation, long term adaptability and economy of resources. Experience from successful applications of Open Building in e.g. Finland, the Netherlands and Japan, could be further explored and adapted in the demonstration project.

9.3 CONCLUSIONS

9.3.1 Important attributes of multi-dwelling buildings – design criteria

It is crucial to balance the costs and the benefits related to design alternatives. Thus, the functional quality options – design criteria - should be clear and their lifetime consequences predicted. Performance objectives should preferably be expressed in standardised performance classes, and, when possible, as functional rather than prescriptive criteria.

The selection of attributes in this work was based on the EU Construction Product Directive. This was expanded, according to the choice of the author, with, for instance, economy and environmental burden. This set of requirements is not claimed to be the only way of defining requirements on buildings, and it is envisaged that a client may want to establish a modified list. Certain attributes are partly redundant, such as energy use and environmental burden. In some cases it is difficult to draw a distinct line between aspects, for example, robustness, mechanical resistance and durability. Some attributes are easy to target and/or quantify such as the fire safety classification or life cycle cost. Other attributes, for example, certain indoor climate aspects or robustness are addressed in qualitative terms.

A set of functional design criteria with regard to the attributes was compiled, and classified in three quality levels. This is a key feature of the ILCD toolbox.

9.3.2 Concrete and the important attributes of buildings

The basic properties of reinforced concrete are high density, high strength, high formability, high thermal conductivity, high heat capacity, inorganic composition, low production cost and low embodied energy content. Referring to the attributes of dwelling buildings this can be translated to:

- Positive characteristics such as: High strength and load carrying capacity, fire and moisture safety, good sound insulation, high thermal mass that can provide comfortable indoor temperatures and decrease the required energy for heating, high durability and robustness in a broad sense.
- Negative characteristics such as: high self-weight, high thermal conductivity that gives heat bridges if not carefully designed, a sturdiness that makes it difficult to change the position of a component after construction.

Concrete is thus a multifunctional material that relates favourably to the required attributes of the primary parts (Support) of a building, cf. Figure 3.4, while other materials may be more suited to use in the secondary and tertiary systems.

It is shown that a relatively small extra effort is needed, for concrete structures, to take the step from minimum requirements, according to norms, to high functional quality. This requires, however, that the properties of concrete and its interaction with the adjoining materials and systems are understood and observed.

9.3.3 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. However, the information is not easily accessible for the designer. One primary objective of this work and thus for developing the ILCD toolbox, was to overcome that obstacle.

Conventional LCC calculations estimating present values, or annualised costs, can be applied throughout 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 that may occur. Reliable input data, for instance with regard to maintenance costs for components and materials, are available from the facilities management sector. Some further work to obtain a broad and reliable database on maintenance of building components and materials would be valuable. To allow also environmental performance assessment environmental data should be introduced.

For the long time perspectives, relevant at design of residential buildings, the choice of interest rates for calculations can be based on average rates for a sufficiently long previous period, for instance 30 years. Uncertainties about the relation between the price increase of a specific item and inflation can be dealt with using sensitivity analysis.

A full environmental assessment of a building, with the LCA method, is still a demanding task, since the necessary quantitative environmental data with regard to 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 process of designing an ordinary dwelling building project. LCA is, however, the logical tool to guide environmental improvement of a product or a process, or to establish quantitative environmental product declarations for single products, or for systems or type buildings. Comparative LCA studies on different structural materials such as concrete, timber or steel show that the differences are small, and that the preferred type of material varies with the type of project. 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 was thus applied as a proxy for the environmental burden in the simplified environmental assessment method in the

ILCD toolbox developed in this work. A full LCA method was also introduced in the toolbox, however, only covering the concrete building frame.

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% with the programme 'VIP+'. If the programme is used for optimisation, it is crucial that it is capable of appreciating building physical related aspects, such as orientation of windows, airflow and heat capacity. The potential contradiction between low energy consumption and good thermal comfort during summer must be observed. An adequate energy balance programme, such as VIP+, can accommodate this type of analysis. A pilot version of a spreadsheet based energybalance programme, 'Consolis tool', was also applied with promising results.

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 user phase is then still the key environmental issue. Energy is and will also be one of the key items in the life cycle cost perspective, why reliable energy balance calculations will be of utmost importance.

9.3.4 The ILCD toolbox and its application to concrete multi-dwelling buildings

A toolbox was compiled based on publicly available data, existing computing tools and own spread sheet models, that were deemed necessary for a pilot ILCD application to Swedish multi-dwelling buildings.

In order to test the practical applicability of ILCD and the simplified ILCD-toolbox, this was tested in a number of real design cases and in one theoretical desk top-study.

The proposed tool to analyse the client's needs, cf. Figure 3.3, box I, was not tested in any of the real design cases. The relatively complex procedures involved are not deemed appropriate for introduction in an ordinary project. They are deemed to be more suited for the repeat order client or the developer of type building concepts, to establish and maintain generic pre-design specifications. The criteria matrix in Table 5.2 serves as a simplified way to analyse the requirements on the building.

The life cycle appraisal modules, cf. Figure 3.3, box II, proved practical to use and gave results that were easy to interpret.

The multiple attribute decision aid, according to Figure 3.3, box III, was employed for ranking of alternatives in three of the real cases and the desktop study. These examples indicate the possibilities of the method. The user must, however, be aware of the sensitivity of ranking according to multi-attribute decision-making theory. Simplified ranking, whereby LCC and socio-economic calculations are applied to compare alternatives, can be used instead of multi-attribute decision-making.

The feedback routine on indoor climate, compare Figure 3.3, box IV, was tested in one real case, which provided useful information on the achieved indoor climate of the building, and possibilities for improvement of the selected technical solutions and systems. The management of the survey was uncomplicated, and the occupant response rate was good.

9.3.5 Application of ILCD. Findings about the method and potential improvements of buildings

About half the life cycle cost refers to the operational phase, of which periodic maintenance and heating are the most important items. These are to a great extent dependent on the design of the building.

The total life cycle costs for the alternative structural and technical designs in the theoretical example in Chapter 6, the test projects in Chapter 7, indicated relatively small differences. This can be explained by the facts that in the context of the whole building the impact was limited, of the specific structures that were altered or that the alternatives were relatively similar. In other cases such as mechanical exhaust ventilation versus supply and exhaust ventilation with heat recovery, one alternative is preferred with regard to production cost and periodic maintenance, while the other is superior with regard to energy consumption. Here the combined cost difference is thus small. That leads to the conclusion that the alternative with the preferred functional performance or lowest environmental burden can be selected, without any negative life cycle cost consequence. This result is equally important as if the LCC analysis should point out one preferred alternative.

Energy use during operation could be decreased by as much as 35% by optimising thermal insulation, thermal storage, air tightness and the orientation of windows. Heat recovery on exhaust ventilation can save 20%. Compare application example in Section 7.8. The total energy use is affected less, in relative terms, as it also includes hot tap water, lighting etc. However, the difference is significant, particularly when viewed as present value of costs over the entire life cycle. The environmental lifetime consequences of the energy performance differences are also significant, according to the assessment model in the ILCD toolbox.

The differences with regard to long-term functional performance, between design alternatives, is clearly visualised by the set of design criteria developed. The theoretical example in Chapter 6 indicated that the life cycle cost and environmental burden does not differ significantly between alternatives with high and low functional quality. This leads to the conclusion, similar to that of the ventilation example above, that the functional quality aspects can govern the choice of design.

With the clear analysis of client needs and relation between these and the technical requirements and their lifetime consequences, the decision maker can avoid being trapped by the lowest production cost principle.

9.3.6 Concluding remarks

ILCD can contribute to improved lifetime quality, cost and environmental efficiency of residential buildings. The most important benefits of ILCD are deemed to be that:

- The different functional quality aspects of the building can be systematically addressed. The lifetime quality options are thereby clarified to the client.
- The life cycle cost and environmental burden with regard to the design alternatives can be estimated. The relationship between 'life time price' and 'lifetime performance', for the alternatives, is thereby determined.

Some specific conclusions that can be drawn from this work:

- The toolbox for simplified ILCD is ready for use in its current status or to be further developed and customized.
- The ILCD toolbox or parts of it can be used in several contexts such as:
    - From early phases of ordinary building design.
    - By evaluation of tenders.
    - By development of whole building concepts as well as components.
- When assessing projects designed according to current practice with the ILCD toolbox, the largest potential for improvement of lifetime quality appears to be enhanced energy efficiency. As energy performance is directly linked to indoor climate this is an example where integrated life cycle design is of particular interest. Buildings large share of the total energy use in society and the importance of good indoor climate, further emphazises the importance of these issues.
- The role of concrete in sustainable multi-dwelling buildings is in the primary structure, providing robust load carrying and shielding functions.
- The lifetime quality factors of concrete as well as related prediction tools and methods, have been thouroughly investigated in this work. The findings provide a base for further improvement of buildings.

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ANNEX 4.A Swedish multi-dwelling buildings - Technical background

4.A.1 Structural frame

There are several structural frame concepts available for multi-dwelling buildings. The dominating concrete based systems are presented in Figure 4.A.1. There are several possibilities to combine types of building frame, which makes the mapping of market shares somewhat uncertain. According to an investigation by Mängda (1999), approximately 65% of the Swedish multi-dwelling frames were of type A, including combinations with prefabricated floor slabs. 15% of the frames were of type B, 10 % of type C and 10% of other types, such as steel with lightweight floors or timber frames.

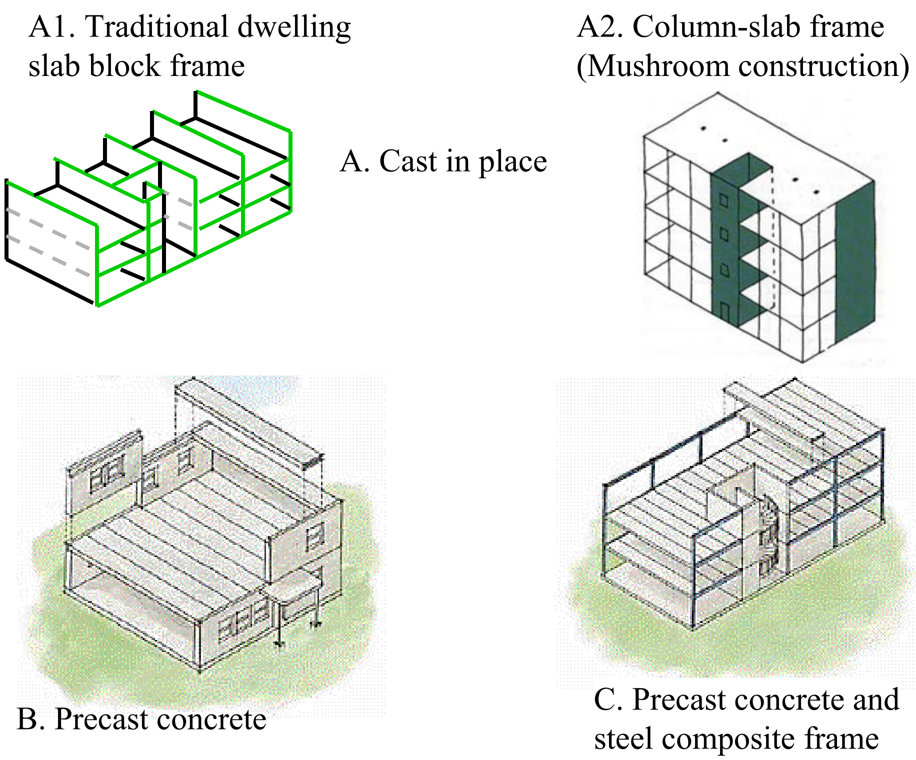


Figure 4.A.1 Typical Swedish multi-dwelling building frames. A2 with permission from the Swedish ready mix concrete association and B and C from Skanska Prefab AB.

<u>Cast in place concrete slab blocks with curtain walls</u>

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 6 m, and 160 to 200 mm in walls. The common structural concept is the slab-block, presented in Figure 4.A.1 ‘A1’. Other types, such as the column-slab frame, adopted from office buildings, according to Figure 4.A.1 ‘A2’, are also used.

The ‘curtain wall’ facades are prefabricated or built on site, with studs of sheet steel or wood, and cladding of bricks or rendering on mineral wool, cf. Annex 6.A.

Precast concrete structure with load carrying sandwich facade 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. This allows spans over the entire width of the building. Compare Figure 4.A.1 ‘B’. The hollow core slabs for residential buildings typically have the profiles 1200x200 or 1200x265 mm, allowing for spans up to 13 m. The elements are produced with extrusion technique, typically on 100 m long beds, and sawn to the specific length. The joints between hollow core slabs are filled with concrete on site. Usually a topping of self-levelling grout, (10-30 mm) 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 consists of sandwich wall panels consisting of an exterior, painted, concrete leave (70 mm), usually with a texture similar to rendering, an insulation layer (100-150 mm) and an internal load carrying concrete leave (100-150 mm).

Systems with short span, reinforced massive floor elements and load carrying internal walls, in a layout according to the in situ cast concrete in Figure 4.A.1 ‘A’, are also used.

Concrete and steel composite structures

Steel and concrete composite structures, were introduced by the end of the 1980’s, 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. The floor are of prefabricated concrete hollow core slabs, as described above, or of massive cast in place concrete, often on prefabricate floor slabs are. For stabilisation, prefabricated, concrete stair enclosures are often used. The facade is a curtain wall similar to that of the in-situ concrete frame, described above, and the interior walls are lightweight structures of plasterboards on sheet steel studs except for the stabilising concrete stair enclosures. Compare Figure 4.1.’C’.

4.A.2 Heating and ventilating systems

For new multi-dwelling buildings there are several systems for heating and ventilation available. The prevailing energy source is district heating (72% of the heated floor area, in 1996, according to SCB (2000). Normally the heating is distributed in the building by hot water radiators. Systems with floor heating or hot air heating have also become technically feasible, since high-insulated windows have eliminated the need for radiators located below windows to avoid condensation on the inner windowpane.

The ventilation systems used in residential buildings are listed in Table 4.A.1 and in Diagram 4.A.1, the market share during different periods is displayed.

Table 4.A.1 Overview of ventilating 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

** According to Hjertén et al (1996)*

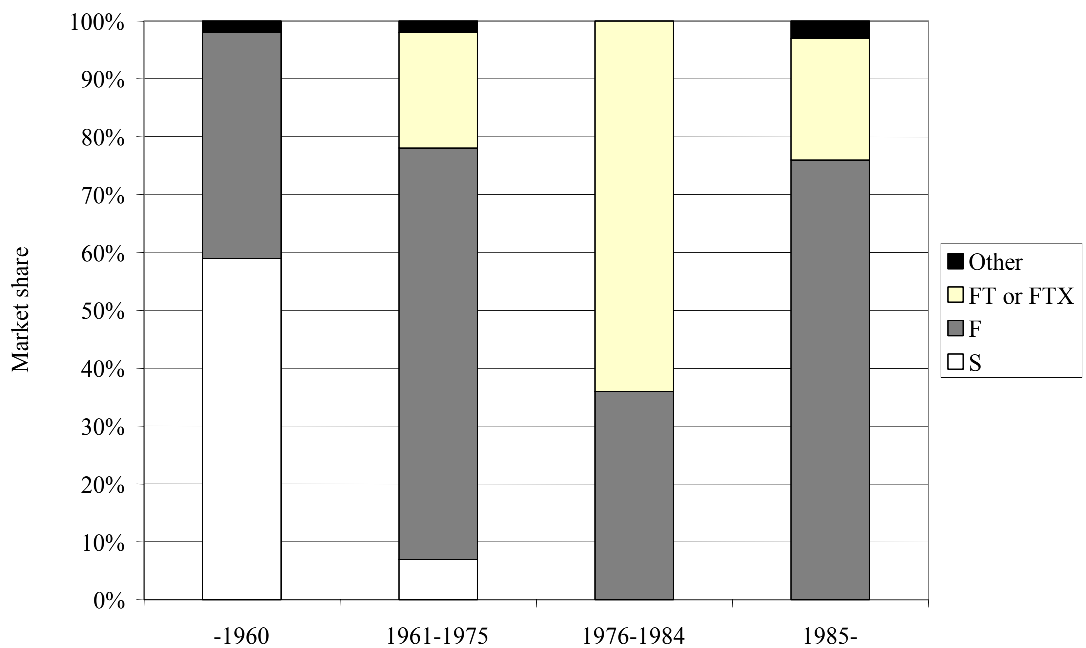


Diagram 4A.1 Distribution of ventilating systems in multi-dwelling buildings in Stockholm distributed by age of building, according to (Engvall and Norrby, 1992), FT or FTX = Mechanical exhaust and supply ventilation, F = Mechanical exhaust ventilation, S = Natural ventilation

The Natural ventilation ('S') uses the thermal driving force whereby the used air leaves the building through the ceiling in exhaust ducts and the fresh air is taken in through valves in the exterior walls or through air leaks. Natural ventilation is very quiet, there is no space 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 to control the ventilation rate. During 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 to modify the natural ventilation in order to improve the performance, such as temperature controlled inlets ('bimetal'), a wind-device on top of the exhaust duct or inlet via snorkels. There is no rational way to obtain heat-recovery with natural ventilation, which of course is a drawback as the ventilation represents one major part in the energy balance of a building. The choice of natural ventilation in the current production of multi-dwelling buildings is restricted to experimental projects.

By 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 high and where the noise from the inlet is the least disturbing. The ventilation rate can be individually controlled by adjusting the inlet valves. 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 performance of buildings with mechanical exhaust ventilation, they can be equipped with heat pumps recovering energy that is used for hot water supply.

One major advantage with the system is that the building is exposed to a constant under-pressure, which ensures safe moisture conditions within the climate shell, as 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 Diagram 4.A.2, 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 can explain this. Good air-tightness of the building and location of the inlets behind radiators in order to avoid inconvenience of cold draughts are prerequisites to obtain good thermal comfort with F-systems. With regard to air quality the perceived difference between F- and FT-systems is insignificant (Engvall and Norrby, 1992), cf. Diagram 4.A.2.

Mechanical supply and exhaust ventilation ('FT' or 'FTX') adds the possibility to condition the supply air by heating, cooling or 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 risks for pollution of 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 preheating of supply air.

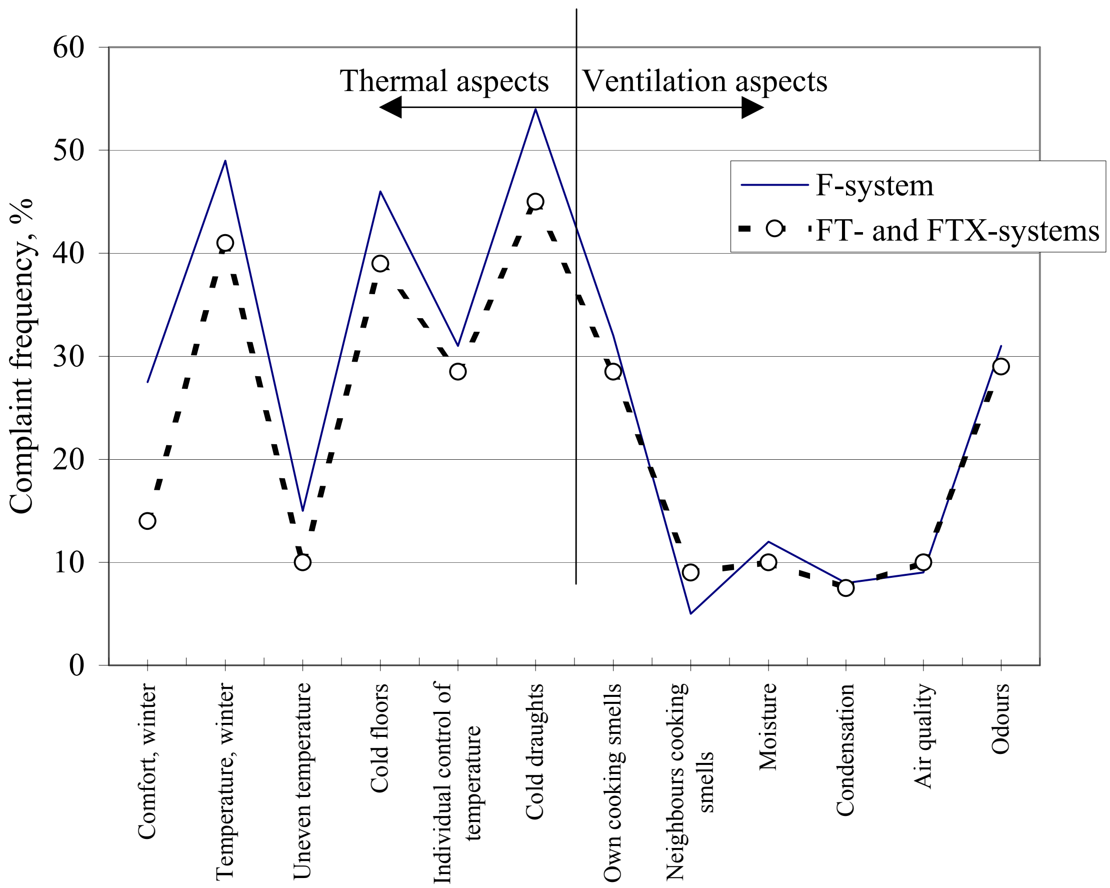


Diagram 4.A.2 Perceived indoor climate quality distributed by type of ventilation system in multi-dwelling residential buildings constructed after 1985 (Engvall and Norrby, 1992)

ANNEX 5.A LCC SPREADSHEET

Table A1. The summary sheet. Example

Life cycle cost and environmental load. Summary sheet

Project:	Parkhouse	Area (m2)
Time horizon (years):	60	1420
Functional unit:	Entire building	
Number of flats:	17	
Real interest rate (%): (or expected rate of return after inflation)	3,0	

Exchange rate €	9,1

	Pricechange rel inflation (%)	ANNUAL COSTS Entire building (€)	ANNUAL COSTS € per m2	NET PRESENT VALUE Entire building (€)	NET PRESENT VALUE € per m2	Share (%)
Administration	0,50	8895	6	274917	194	4,6
Caretaking	0,50	9987	7	308679	217	5,2
Water and sewage	0,50	6710	5	264237	186	4,5
Electricity	1,50	2341	2	92176	65	1,6
Waste disposal	1,50	2153	2	66559	47	1,1
Heating	1,50	13108	9	516184	364	8,7
Insurance	0,50	780	1	24116	17	0,4
Other annual cost	0,50	2965	2	91639	65	1,5
Periodic maintenance	0,50	14195	10	438745	309	7,4
Initial cost (production)	0,50	112883	79	3489065	2457	59,0
Property tax	0,00	5462	4	151151	106	2,6
Value (-) or cost at end of life	0,50	6414	5	198252	140	3,4
Sum		185892	131	5915720	4166	

		Socio economy according to:	EPS 200
Environmental discount rate (%):	0	Exchange rate €	1

Environmental assessment	ANNUAL Entire building (€)	ANNUAL € per m2	TOTAL LIFE CYCLE Entire building (€)	TOTAL LIFE CYCLE € per m2	Share (%)
Production	1400	1	83972	59	14,2
Operation	9859	7	591569	417	87,2
End of life cycle	53	0	3186	2	0,5
Sum	11312	8	678728	478	

	kWh/m2
Annual energy use for heating including hot water	140

Data in shaded boxes to be inserted by the user.

Table A2. Examples of sheets for respective cost items

Administration — Functional unit: Entire building

Parkhouse

Timehorizon N (years)	60	From sheet 'Summary'			
Real interest rate (%):	3,00	From sheet 'Summary'			
Pricechange rel inflation (%)	0,5	From sheet 'Summary'			
=> discount rate	1,025		Selected cost per m2		
Cost. (Todays price SEK)	80 940		57		
Sum present value	2 501 747				
=> annual cost during N years	80 940				

Statistics Sweden (Year 2002)	Stockholm	Gothenburg	Other large communities	Small communities	Average
Semi-public housing conpany	77	69	57	52	61
Other rental flats	30	27	30	22	26
Housing co-operatives	22	16	18	17	20

Heating — Functional unit: Entire building

Parkhouse

Timehorizon N (years)	60	From sheet 'Summary'	
Real interest rate (%):	3,00	From sheet 'Summary'	
Pricechange rel inflation (%)	1,5	From sheet 'Summary'	
=> discount rate	1,015		
Cost. (Todays price SEK)	119 280		Insert either annual energy cost/m2
Sum present value	4 697 278		or
			Estimated energy use/m2 for relevant
=> annual cost during N years	119 280		source below

Average use according to Miljövårdsberedningen, 2000.

kWh/m2	Total
140	198800

	Energy requirement (kWh/year)	Price (SEK/kWh)	
Oil***		0,61	
District heating	198800	0,6	140
Electricity		1	
Natural gas		0,6	
Other source			
	198800		

Statistics Sweden (Year 2002) Cost/m2	Stockholm	Gothenburg	Other large communities	Small communities	Average
Semi-public housing conpany	105	87	87	91	93
Other rental flats	94	85	75	75	79
Housing co-operatives	84	80	68	77	79

Cost for district heating according to EKAN 2003

Multi-dwelling 'EKAN' type building: 1000 m2 with 15 flats

Price level 2003	Total	193000 kWh
Swedish average	112,4	
Highest (Lerum)	143	
Lowest (Luleå)	72	

Data in shaded boxes to be inserted by the user.

Table A3. Sheets for calculation of periodic maintenance. Example

PERIODIC MAINTENANCE									
				Time horizon (y):	60	Real interest rate:			3,00%
				Number of flats:	17	Cost increase relative inflation:			0,50%
				Area m2:	1420	Discount rate:			1,025
		Amount	Cost	Cost/activity	Interval	Annual cost	Annual cost	Present value	Present value
		Number/m2	SEK	SEK	Years	SEK	SEK/Area	SEK	SEK/Area
	Total →					**129 577**	91	**4 005 049**	**2 820**
Group									
A	Interior surfaces								
	Wall and ceiling								
	Repaint basement	34	160	5440	0	0	0,0	0	0,0
	Repaint flat	17	25800	438600	13	27108	19,1	837866	590,0
	Repaint laundry room		285	0	13	0	0,0	0	0,0
	Repaint staircase	1	35600	35600	15	1724	1,2	53271	37,5
						0		0	
A2	Floors					0		0	
	Plastic carpet exch.		225	0	17,5	0	0,0	0	0,0
	Linoleum exch.		255	0	22,5	0	0,0	0	0,0
	Laminate exch.		370	0	22,5	0	0,0	0	0,0
	Ceramic tiles exch.		615	0	30	0	0,0	0	0,0
	Plastic carpet bath.		620	0	22	0	0,0	0	0,0
	Parquet rubbing	2000	100	200000	17,5	8697	6,1	268805	189,3
	Parquet exchange	2000	400	800000	45	8520	6,0	263340	185,5
	Repaint concrete floor		80	0	15	0	0,0	0	0,0
						0		0	
A3	Fittings and furnishings					0		0	
	Kitchen shutters excl	17	7200	122400	35	1669	1,2	51576	36,3
	Kitchen desks exch.	17	600	10200	20	324	0,2	10024	7,1
						0		0	
A4	Sanitary installations					0		0	
	Sink	17	2760	46920	40	565	0,4	17474	12,3
	Toilett	34	2550	86700	32,5	1257	0,9	38859	27,4
	Washbasin	34	1600	54400	32,5	789	0,6	24382	17,2
	Bathtub	17	5950	101150	32,5	1467	1,0	45336	31,9
						0		0	
A5	Electrical installations					0		0	
	Refrigirator/freezer	17	4725	80325	13,5	4837	3,4	149514	105,3
	Stove	17	4500	76500	17,5	3327	2,3	102818	72,4
	Stove - fan	17	1850	31450	32,5	456	0,3	14096	9,9
	Washing macine flats		4880	0	12	0	0,0	0	0,0
	Dryer flats		3220	0	12	0	0,0	0	0,0
	Washing macine com	1	27300	27300	11	2102	1,5	64981	45,8
	Dryer common	1	13440	13440	11	1035	0,7	31991	22,5
A6	Radiators								
	Exchange	102	1920	195840	45	2086	1,5	64466	45,4
	Repaint	102	163	16626	15	805	0,6	24879	17,5
A7	Other furnishings								
	Sundries	17	8896	151232	40	1822	1,3	56323	39,7
	Bathroom equipment	17	550	9350	15	453	0,3	13991	9,9
						0		0	
A8	Doors					0		0	
	Doors in flats, exch	85	2850	242250		0	0,0	0	0,0
	Repaint doors	85	520	44200	20	1405	1,0	43435	30,6
	Doors to flats exch.	17	6750	114750		0	0,0	0	0,0
								0	
B	Secondary areas					0		0	
B1	Lifts	1	275000	275000	30	4242	3,0	131104	92,3
B6	Waste disposal	1	10600	10600	15	513	0,4	15862	11,2
B7	Locks and keys	17	430	7310	20	232	0,2	7184	5,1
B8	Common space		148	0	22,5	0	0,0	0	0,0
B9	Laundry room	21	245	5145	11,5	384	0,3	11880	8,4

C	Eletricity and phones					0		0	
	El.-system in flats. E	17	65	1105	30	17	0,0	527	0,4
C1	Control systems	1		0		0	0,0	0	0,0
C2	Fuse panels, ets.	1	1899	1899	30	29	0,0	905	0,6
C3	Tele and TV	17	310	5270	20	168	0,1	5179	3,6
C4	Power supply			0		0	0,0	0	0,0
D	Climate systems					0		0	
	Radiators check	1420	10	14200	10	1163	0,8	35949	25,3
	Hot-water boiler	1	24500	24500	15	1186	0,8	36661	25,8
	Heat exchanger wate	1	30900	30900	20	982	0,7	30365	21,4
	Expansion tank	1	10050	10050	20	320	0,2	9876	7,0
	Circulation pump		8700		20			0	
D1	District heating contr	1	168000	168000	30	2591	1,8	80093	56,4
D2	Exhaust air fan	2	31400	62800	22,5	1835	1,3	56703	39,9
	Supply air fan	0	22400	0	22,5	0	0,0	0	0,0
	Heat exchanger air	0	3000	0	20	0	0,0	0	0,0
	Heat recovery equipr	1	25700	25700	20	817	0,6	25255	17,8
D3	Ventilation inspectior	1420	5	7100	3	2256	1,6	69738	49,1
	Adjustment exhaust	34	20	680	20	22	0,0	668	0,5
	Adjustment supply fa	34	20	680	20	22	0,0	668	0,5
D4	Exchange other vent	34	340	11560	22,5	338	0,2	10438	7,4
D6	Piping	17	43200	734400	40	8849	6,2	273513	192,6
D7	Ducts	0		0	30	0	0,0	0	0,0
D8	Control systems	0	17000	0	16	0	0,0	0	0,0
E	Water and sewage					0		0	
E1	Plumbing	17	55700	946900	45	10084	7,1	311695	219,5
				0		0	0,0	0	0,0
				0		0	0,0	0	0,0
				0		0	0,0	0	0,0
						0	0,0	0	0,0
G	Building structures					0	0,0	0	0,0
H	Climate shell					0	0,0	0	0,0
H1						0	0,0	0	0,0
H2	Windows and doors			0		0	0,0	0	0,0
	Windows exchange	102	6600	673200	35	9178	6,5	283667	199,8
	Doors exchange	2	15000	30000	35	409	0,3	12641	8,9
	Entrance, exc.	1	23200	23200	35	316	0,2	9776	6,9
	Repaint entrance	1	630	630	8,5	67	0,0	2077	1,5
H3	Balconies					0		0	
	Concrete	17	22000	374000	50	3520	2,5	108812	76,6
				0		0	0,0	0	0,0
H4	Facades					0		0	
	Rendering, 15 % ren	700	240	168000	30	2591	1,8	80093	56,4
	Rendering, additiona	700	310	217000	60	1612	1,1	49810	35,1
	Facades washing	0	70	0	28	0	0,0	0	0,0
	Repaint, silicate colo	0	70	0	17	0	0,0	0	0,0
	Brick facade, renov.	0	135	0	40	0	0,0	0	0,0
	Wood panel, exchan	0	270	0	35	0	0,0	0	0,0
	Wood panel, repaint	0	75	0	8,5	0	0,0	0	0,0
H5	Roof					0		0	
				0		0	0,0	0	0,0
	Terrassed roof	0	600	0	42	0	0,0	0	0,0
	Sheet steel exchang	400	700	280000	42,5	3172	2,2	98038	69,0
	Concrete tiles exchar	0	320	0	32,5	0	0,0	0	0,0
	Roof felt, exch	0	200	0	27,5	0	0,0	0	0,0
				0		0	0,0	0	0,0
	Exch. roof details	400	150	60000	27,5	1484	1,0	45855	32,3
H6	Eaves, gutter	140	360	50400	32,5	731	0,5	22589	15,9
H7				0					

Statistics Sweden Year 2002	Stockholm	Other large communities	Small communities	Average
Semi-public housing conp	175	163	135	151
Other rental flats	154	125	98	128
Housing co-operatives	37	33	35	36

Note: By co-operative tenure the periodic maintenanceinside flat is not included in the statistics

Table A4. End of life cycle. Example

End of life-cycle Functional unit: Entire building

Project:	Parkhouse		
Time horizon (years):	60		
Real interest rate (%):	3		
Pricechange rel inflation (%)	0,50		
=> discount rate	1,025		
Residual value or cost	7 937 623	Insert calculated value or cost or apply scenario examples below	
Sum present value	1 804 091		
=> annual cost during N years	58 368		

Scenario

Insert value or cost in relation to cost of new production		-0,25
Examples:		
Value equal to new production:	1	
Cost for demolition and final disposal = 25 % of new production:	-0,25	

Environmental load of demolition and final disposal:
This is normally only applied together with the 'negative' cost scenario above
in other cases set this box = 0 : 1

Demolition and disposal accoding to
Björklund et al 1996 Weight/m2 for concrete residential building: 800 kg
page 112-113

Energy source	Energy requirement (kWh)	kWh/m2
Diesel	20314	14

Transport 30 km
Diesel

Emission/resource use for 30 ton,km:		per m2	per project
Energy - Diesel (kWh)	8,3	7	9467

(LCAiT, 1996, generic data: Diesel truck, full)

ANNEX 5.B Energy balance calculation according VIP+ (2002) Result summary sheet. Example. (Printout in Swedish)

INDATA
Allmänt

Beräkningsdatum:	2005-01-26 Tid: 10:59:42
Beräkningsperiod - Dag:	1 - 365
Klimatdata:	STOCKHOLM
Byggnadens läge:	ÖPPET
Markreflektion:	0.70
Vindreduktion:	0.90
Horisontvinkel mot markplan:	5 °
"Söderfasadens" vinkel mot söder:	0 °
Verksamhetstyp:	Bostad
Antal lägenheter:	16
Skalfaktor ventilation:	1685 m³
Uppvärmd bruksarea enl SS021052:	648 m²

Aktuellt Hus

Byggdelstyper - Katalog:

Byggdelstyp	Material	Skikt-tjocklek m	Värme-lednings-tal W/m²°C	Densitet kg/m³	Värme-kapacitet J/kg°C	U-värde W/m²°C	Delta-U-värde W/m²°C
lättinnerv	RGLMU-44	0.200	0.044	788	868	0.132	0.020
	RGLMU-44	0.120	0.044	788	868		
	GIPSSKIVA	0.026	0.220	900	1100		
BTG200	BETONG	0.200	1.700	2300	800	3.476	0.020
BTG230	BETONG	0.230	1.700	2300	800	3.276	0.020
Golvyttrepilsbo	MARK1.0	1.000	1.000	1800	800	0.223	0.020
	CELLPLAST2	0.120	0.040	25	1400		
	BETONG1.7	0.150	1.700	2300	800		
	KORKISOL	0.005	0.080	175	1800		
	TRÄ-13	0.020	0.130	500	2500		
Golvinrepilsbo	MARK3.4	1.000	0.290	1800	800	0.144	0.020
	CELLPLAST2	0.120	0.040	25	1400		
	BETONG1.7	0.150	1.700	2300	800		
	KORKISOL	0.005	0.080	175	1800		
	TRÄ-13	0.020	0.130	500	2500		
YVputsPilsb	KCBRUK	0.010	1.000	1800	800	0.195	0.020
	RGLMU-44	0.170	0.044	788	868		
	RGLMU-44	0.045	0.044	788	868		
	GIPSSKIVA	0.013	0.220	900	1100		
Ytaklättpilsbo	RGLMU-44	0.440	0.044	788	868	0.098	0.020
	GIPSSKIVA	0.013	0.220	900	1100		

Byggnadsdelar - Väggar, bjälklag

Benämning	Byggdelstyp	Orientering	Area m²	Sol-absorb-tion	Form-faktor vind	---Nivåer--- Lägsta m	Högsta m	Luftläckage q50 50Pa m³/m²h	expo-nent	Mot-temp °C
innerVÄGG	lättinnerv	INNER	686.0							
LGHskiljv	BTG200	INNER	437.0							
mellanbjälklag	BTG230	INNER	648.0							
golv på mark	Golvyttrepilsbo	JORD	118.0	0.00	0.0	0.0	0.0	0.00	0.00	
golv på mark	Golvinrepilsbo	JORD	213.0	0.00	0.0	0.0	0.0	0.00	0.00	
yttervnorr	YVputsPilsb	NORR	29.6	0.70	-0.6	0.0	2.6	2.00	0.65	
yttervnat	YVputsPilsb	SÖDER	29.6	0.70	-0.6	0.0	2.6	2.00	0.65	
yttervgväst	YVputsPilsb	VÄSTER	172.0	0.70	0.7	0.0	2.6	2.00	0.65	
yttervgöst	YVputsPilsb	ÖSTER	240.0	0.70	-0.5	0.0	2.6	2.00	0.65	
yttertak	Ytaklättpilsbo	TAK	324.0	0.00	0.0	0.0	2.6	2.00	0.65	

Byggnadsdelar - Fönster dörrar ventiler

Benämning	Byggdelstyp	Orien-tering	Area m²	Glas-andel %	Skuggfaktor F1 %	F2 %	U-värde W/m²°C	Form-faktor vind	-Nivåer- Lägst m	Högst m	Luftläckage q50 50Pa m³/m²h	Expo-nent
FÖNSTöst	3GLAS1.4	ÖSTER	6.4	80	75	60	1.40	-0.5	1.0	2.5	3.00	0.60
FÖNSTväst	3GLAS1.4	VÄSTER	104.8	80	75	60	1.40	0.7	1.0	2.5	3.00	0.60
ydöst	Pilsboyd	ÖSTER	33.6	15	75	60	1.40	-0.5	0.0	2.1	3.00	0.65
FÖNSTnorr	3GLAS1.4	NORR	1.6	80	75	60	1.40	-0.6	1.0	2.0	3.00	0.60
FÖNSTnsöd	3GLAS1.4	SÖDER	1.6	80	75	60	1.40	-0.6	1.0	2.0	3.00	0.60

Driftdata

Driftfalls-benämning	Vecko-dagar	Dag-nummer	Tid	Tilluft oms/h	Frånluft oms/h	Process-energi W/m²	Person-värme W/m²	Maxtemp °C	Mintemp °C
BOST-F-21	MÅND-SÖND	1-365	0-8	0.00	0.46	5.00	0.00	27.00	21.00
BOST-F-21låg	MÅND-SÖND	1-365	8-16	0.00	0.14	5.00	0.00	27.00	21.00
BOST-F-21	MÅND-SÖND	1-365	16-24	0.00	0.46	5.00	0.00	27.00	21.00

Installationer:

	Tryckhöjning Pa	Verkningsgrad %
Tilluftsfläkt	1	70.00
Frånluftsfläkt	200	70.00

Värmepump Kondensoreffekt 0 W
Värmepump Värmefaktor 1.00
Värmeväxlare Energiverkningsgrad 0 %
Inget krav på energisparåtgärder enligt BBR kap 9:3
Lägsta tilluftstemperatur 18.00

Energiförbrukning för tappvarmvatten
Energiförbrukning per lägenhetsarea 2.05 W/m²
Energiförbrukning per lägenhet 205.0 W/lgh
Värmeåtervininning från spillvatten till tappvarmvatten
Verkningsgrad 0.00 %

RESULTAT

Aktuellt Hus

Period	Avgiven energi kWh Trans-mission	Luft-läckning	Venti-lation	Varm-vatten	Kyl-ning	Tillförd energi kWh Sol-energi	Åter-vinning	Process Person	Upp-värmning
Månad 1	6593	210	3266	3429	0	415	0	2411	10698
Månad 2	5972	249	3010	3097	0	1044	0	2177	9110
Månad 3	6631	198	3457	3429	0	2212	0	2411	9112
Månad 4	4663	137	2696	3318	0	3762	0	2333	4804
Månad 5	3289	115	2268	3429	2736	6392	0	2411	3476
Månad 6	2408	71	1854	3318	4470	6429	0	2333	3352
Månad 7	1732	48	1489	3429	5070	5876	0	2411	3464
Månad 8	2298	70	1646	3429	3248	4751	0	2411	3464
Månad 9	3393	73	1988	3318	207	2758	0	2333	3475
Månad 10	3852	123	2113	3429	0	1634	0	2411	5458
Månad 11	5747	253	2896	3318	0	591	0	2333	9277
Månad 12	6003	229	2972	3429	0	248	0	2411	9962

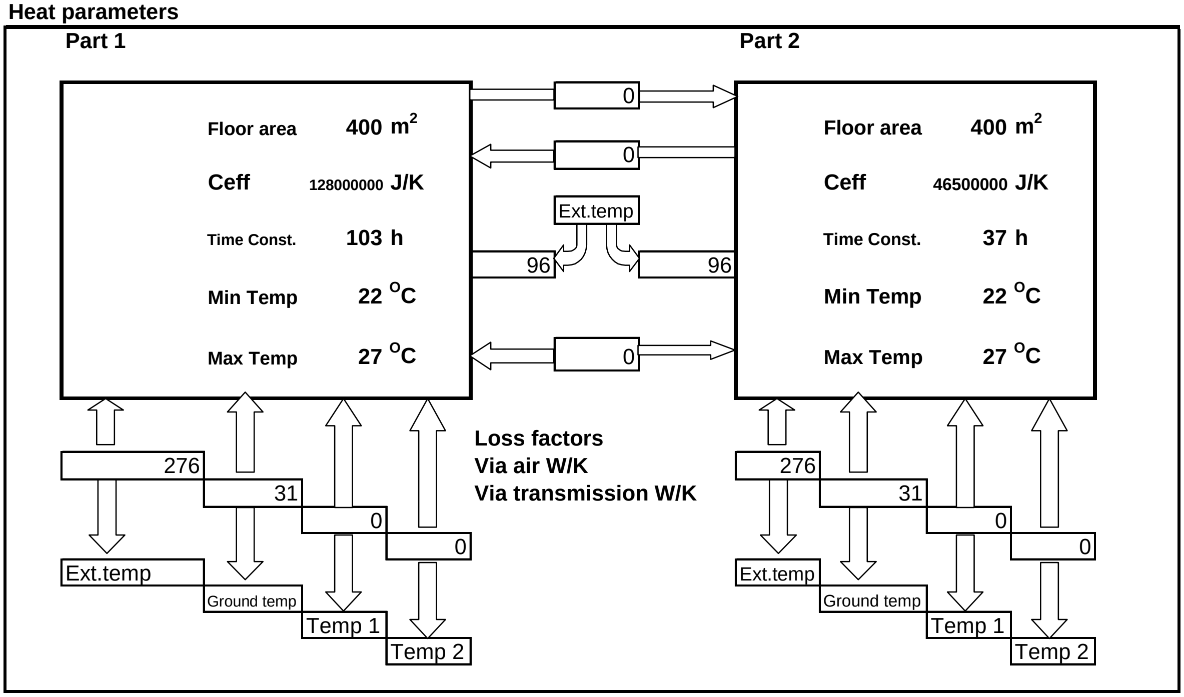
ANNEX 5.C Energy balance calculation according to the Consolis tool (Johannesson 2004). Result summary sheet. Example

Part 1 and 2 can either be two different temperature zones in the specific building, or two different design alternatives of one building. In this example Part 1 is a heavy alternative and Part 2 a lightweight alternative of the same building. The difference in energy use is related to the difference in thermal mass. This is also indicated by the 'time constant'.

Calculated yearly energy consumption
Parkhusen. Malmö
Clim Malmö

	Part1				Part2			
Heated floor area	400	m^2			400	m^2		
Energy need for heating	21584	kWh/a	54	kWh/m^{2}a	23305	kWh/a	58	kWh/m^{2}a
Property- and household electricity	22000	kWh/a	55	kWh/m^{2}a	22000	kWh/a	55	kWh/m^{2}a
Hot water	18000	kWh/a	45	kWh/m^{2}a	18000	kWh/a	45	kWh/m^{2}a
Total	61584	kWh/a	154	kWh/m^{2}a	63305	kWh/a	158	kWh/m^{2}a
Surplus energy (indication)	2606	kWh/a	7	kWh/m^{2}a	2606	kWh/a	7	kWh/m^{2}a

Heat parameters



ANNEX 5.D Calculation sheets included in model for computation of socio-economic cost related to energy use. Examples

Table D.1 Emission factors for energy carriers and related socio-economic cost

	Emissionsfactors for C			ELU/kg	Emissionsfactors for N			ELU/kg	Emissionsfactors for SO			ELU/kg	Energy-resource use		
	U*	G**	Total	0,108	U*	G**	Total	2,13	U*	G**	Total	3,27	Total		**ELU**
Oil				Euro				Euro				Euro	ELU/MJ	0,0094	Euro
g/MJ	77,9	15	92,9	0,010	0,16	0,08	0,240	0,001	0,306	0,098	0,404	0,001		0,009	**0,021**
g/kWh	280,4	54,0	334,44	0,036	0,6	0,3	0,865	0,002	1,1	0,4	1,453	0,005		0,034	**0,077**
Electricity. Swedish mix													ELU/MJ	0,001	
g/MJ		11,9	11,9	0,001		0,019	0,019	0,000		0,012	0,012	0,000		0,001	**0,002**
g/kWh	0,0	42,8	42,84	0,005	0,0	0,1	0,068	0,000	0,0	0,0	0,045	0,000		0,003	**0,008**
District heating. Swedish mix***													ELU/MJ	0,005	
g/MJ		32,9	32,9	0,004		0,089	0,089	0,000		0,084	0,084	0,000		0,005	**0,009**
g/kWh	0,0	118,4	118,44	0,013	0,0	0,3	0,321	0,001	0,0	0,3	0,302	0,001		0,017	**0,031**
Natural gas													ELU/MJ	0,009	
g/MJ	59	3,1	62,1	0,007	0,05	0,015	0,062	0,000	0,0005	0,0002	0,001	0,000		0,009	**0,016**
g/kWh	212,4	11,2	223,56	0,024	0,2	0,1	0,223	0,000	0,0	0,0	0,003	0,000		0,034	**0,058**
Diesel trucks													ELU/MJ	0,0094	
g/MJ	73	10,8	83,848	0,009	0,73	0,068	0,798	0,002	0,023	0,07	0,094	0,000		0,009	**0,020**
g/kWh	262,9	38,9	301,853	0,033	2,6	0,2	2,871	0,006	0,1	0,3	0,337	0,001		0,034	**0,073**
Other													ELU/MJ	0	
g/MJ			0	0,000			0,000	0,000			0,000	0,000		0,000	**0,000**
g/kWh	0,0	0,0	0	0,000	0,0	0,0	0,000	0,000	0,0	0,0	0,000	0,000		0,000	**0,000**

*U: Combustion/utilisation
*G : Extraction/generation

*** District heating	Proportion
- Renewable fuel: 24.2 %.	0,242
- Electricity: 12.7 %.	0,127
- Oil: 12.0 %.	0,12
- Peat: 8.2 %.	0,082
- Hard coal: 7.7 %.	0,077
- Natural gas: 7.0 %.	0,07
- Other heat production (2): 28.2 %.	0,282

	Proportion
Fossil	0,486
Electricity	0,177
Renewable	0,337
	1

Table D.2 Computation of socio-economic cost based on input on use of specific energy sources

Environmental consequences of energy use						
Project:		Environmental discount factor:		1		Time horizon (years):
Parkhouse						60
	Energy use kWh	CO2 kg	NOX g	SO2 g	VOC g	Socio economy ELU
Production						
Oil***	0	0	0	0	0	0
Electricity. Swedich mix	710000	30416	48053	31694	20	8010
Diesel trucks	710000	214315	2038410	239242	66	75963
Sum production	1420000	244732	2086463	270936	86	83972
Operation						
Oil***	0	0	0	0	0	0
District heating. Swedisl	11928000	1412752	3834613	3607027	96	577151
Electricity. Swedish mix	1278000	54750	86495	57050	37	14418
Natural gas	0	0	0	0	0	0
Other	0	0	0	0	0	0
Sum operation	13206000	1467502	3921108	3664077	132	591569
End of life cycle						
Electricity. Swedish mix		0	0	0	0	0
Diesel trucks	29781	8989	85500	10035	3	3186
Sum end of life cycle	29781	8989	85500	10035	3	3186
Total	**14655781**	**1721223**	**6093071**	**3945048**	**221**	**678728**

ANNEX 5.E Sheets for data input and output from 'LCAiT'. Examples

Input data: Crossection and material volumes.
Here: 1 m2 of a 220 mm thick slab

	Case		
	A1	A2	A3
Reinforcement kg/m3	30	30	30
Crossection or height (m2 or m)	0,22	0,22	0,22
Lenght/area (m or m2)	1	1	1
Volume (m3)	0,22	0,22	0,22
Reinforcement/unit (kg)	*6,6*	*6,6*	*6,6*

Input data: Concrete. Here three different concrete grades

Concrete recipe kg/m3	A1	A2	A3
Concrete grade	C32/40	C40/50	C25/30
cement	333	345	275
water	200	173	193
aggreg crush	1000	1000	1000
aggreg natural	863	879	929
reinforcement			
addmixtr	4	4	4
Total weight/m3	2400	2400	2400
Proportions (Input to LCAiT)	A1	A2	A3
cement	0,139	0,144	0,115
water	0,083	0,072	0,080
aggreg crush	0,417	0,417	0,417
aggreg natural	0,360	0,366	0,387
	0,000	0,000	0,000
addmixtr	0,002	0,002	0,002
Reinforcement kg/m3	30,00	30,00	30,00
proportion reinforcem/concrete	0,0123	0,0123	0,0123

Output data: Environmental stressors calculated by 'LCAiT' per kg concrete

Insert results of LCI computed by LCAiT			
NO_x (g/kg)	0,29	0,30	0,26
SO_2 (g/kg)	0,07	0,08	0,06
CO_2 (g/kg)	117	123	101
Energy use (MJ/kg)			
Fossil fuel	0,53	0,55	0,46
Electricity	0,25	0,26	0,24
Waste fuels	0,14	0,14	0,11
MJ/ton	905	947	812
kWh/ton	251	263	226

Output data: Environmental stressors per functional unit. Here 1 m2 of a 220 mm thick slab

Stressors per unit	A1	A2	A3
NOx g/unit	152	159	137
SO2 g/unit	38	41	34
CO2 g/unit	62334	65750	54187
Energy use MJ/unit			
Fossil fuel	281	295	248
Electricity	131	136	127
Waste fuels	72	75	60
Total energy	484	506	434

Aggregated environmental load for the three different alternatives according to the Selected valuation model; Here EPS 2000

	Valuation according to: EPS 2000			
	ELU/g	ELU/functional unit		
		A1	A2	A3
NOx	0,0021	0,320	0,335	0,289
SO2	0,0033	0,125	0,135	0,113
CO2	0,0001	6,732	7,101	5,852
	ELU/MJ			
Fossil fuel	0,0094	2,630	2,765	2,319
Electricity	0,0009	0,115	0,120	0,111
Waste fuels	0	0,000	0,000	0,000
Total		9,9	10,5	8,7

ANNEX 5.F Environmental data for concrete LCA model

	Energy use (MJ/kg)	Transport to next process	km	Emissions to air (g/kg)[13]		Reference
Natural aggregates		Heavy truck	1			Vold and Rönning (1995)
Electricity	0,0036			CO_2	3,017	
Light oil	0,0171			NO_x	0,0303	
Diesel mach	0,0183			SO_2	0,0030	
Crushed aggregates		Heavy truck	1			Vold and Rönning (1995)
Electricity	0,0216			CO_2	3,242	
Light oil	0,0171			NO_x	0,0310	
Diesel mach	0,0183			SO_2	0,0033	
Cement		Heavy truck. (From depot to concrete plant)	40			Cementa (2003)[14]
Electricity	0,48			CO_2	710	
Fossil fuel	2,86			NO_x	1,25	
Waste fuel	0,90			SO_2	0,35	
Admixtures		Medium truck	100			Perstorp (1997)
Electricity	0,1			CO_2	1300	
Diesel	8			NO_x	2,5	
Unspecified	1,3			SO_2	0,13	
Concrete		Medium truck	10			Björklund et. al (1996).
Electricity	0,0151			CO_2	0,77	
Oil light	0,00685			NO_x	0,0009	
				SO_2	0,0008	
Reinforcement steel		Heavy truck	100			Björklund et. al (1996).
Electricity	2,68			CO_2	697	
Diesel	0,125			NO_x	1,22	
Naturgas	3,2			SO_2	0,94	
Oil light	1,49					
Building site						Björklund et. al (1996).
Electricity	0,127			CO_2	3,665	
Diesel	0,025			NO_x	0,0416	
				SO_2	0,0035	

Transport energy use	MJ/kg,km		Empty return is included for all transports
	Full	Empty	
Heavy truck, full	0,00051	0,000360	
Medium truck, full	0,00100	0,000746	

[13] Refers to the total emissions for production of material, or in case of concrete and building site from specific energy use of process step. Transport to next step in process is not included.
[14] Weighted mean value for three cement plants. Ship transport to depot included.

ANNEX 5.G 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**

ANNEX 5.H Comparative energy balance calculations with VIP+ (2000) and the Consolis tool (2004)

A theoretical building with simple geometry was defined, cf. Figure 5.H.1.

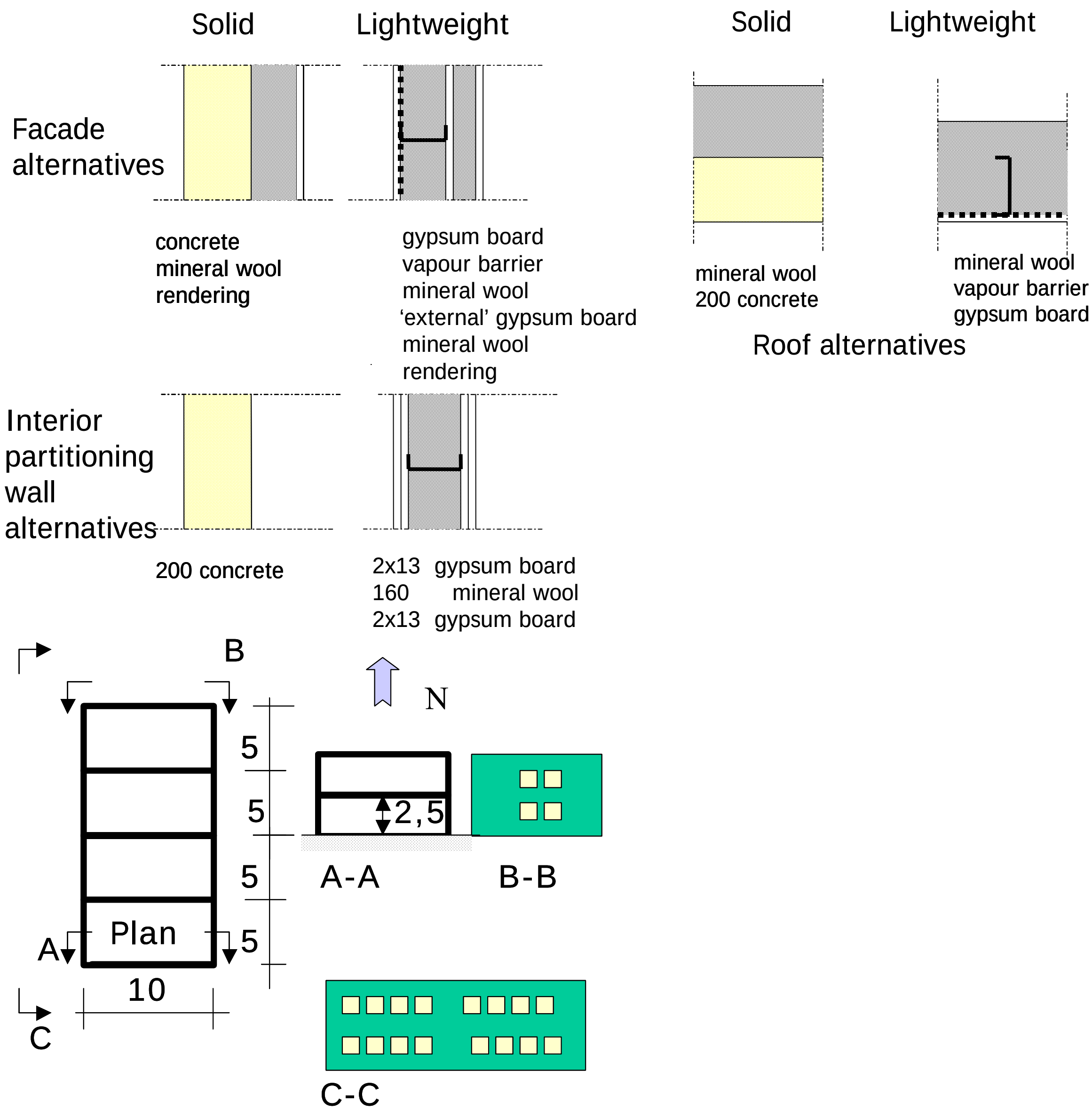


Figure 5.H.1 Geometrical layout and structural outline for comparative energy balance calculation

Two alternative structures were compared:

- 'S' Solid with external walls and roof as well as internal partition walls and floor in concrete.
- 'L' Lightweight structures.

Both cases have concrete slab on ground.

Ventilation regime: 0,5 air changes per hour constantly.

Table 5.H.1 Specification of areas and U-values

Structure	Area (m^2)	U-value (W/m^2°C)		
Ground slab	200	0,15		
Roof	200	0,18		
Interior floor	200			
Interior wall	150		Window area (m^2)	U-value (W/m^2°C)
Net façade:				
North	44/50*	0,25	6/0*	1,8
East	76/100*	0,25	24/0*	1,8
West	44/50*	0,25	6/0*	1,8
South	76/40*	0,25	24/60*	1,8

** First figure: Normal case. Second figure: Case with all windows facing to the south*

In order to assess the effect of solar radiation through the windows two different orientations of the building were examined. One case with the long sides facing in the East-West direction with 10% of the total window area towards North and South and 40% of the total window area towards East and West, 'E/W'. The other case has the same total window area but all windows are facing to the South, 'S'.

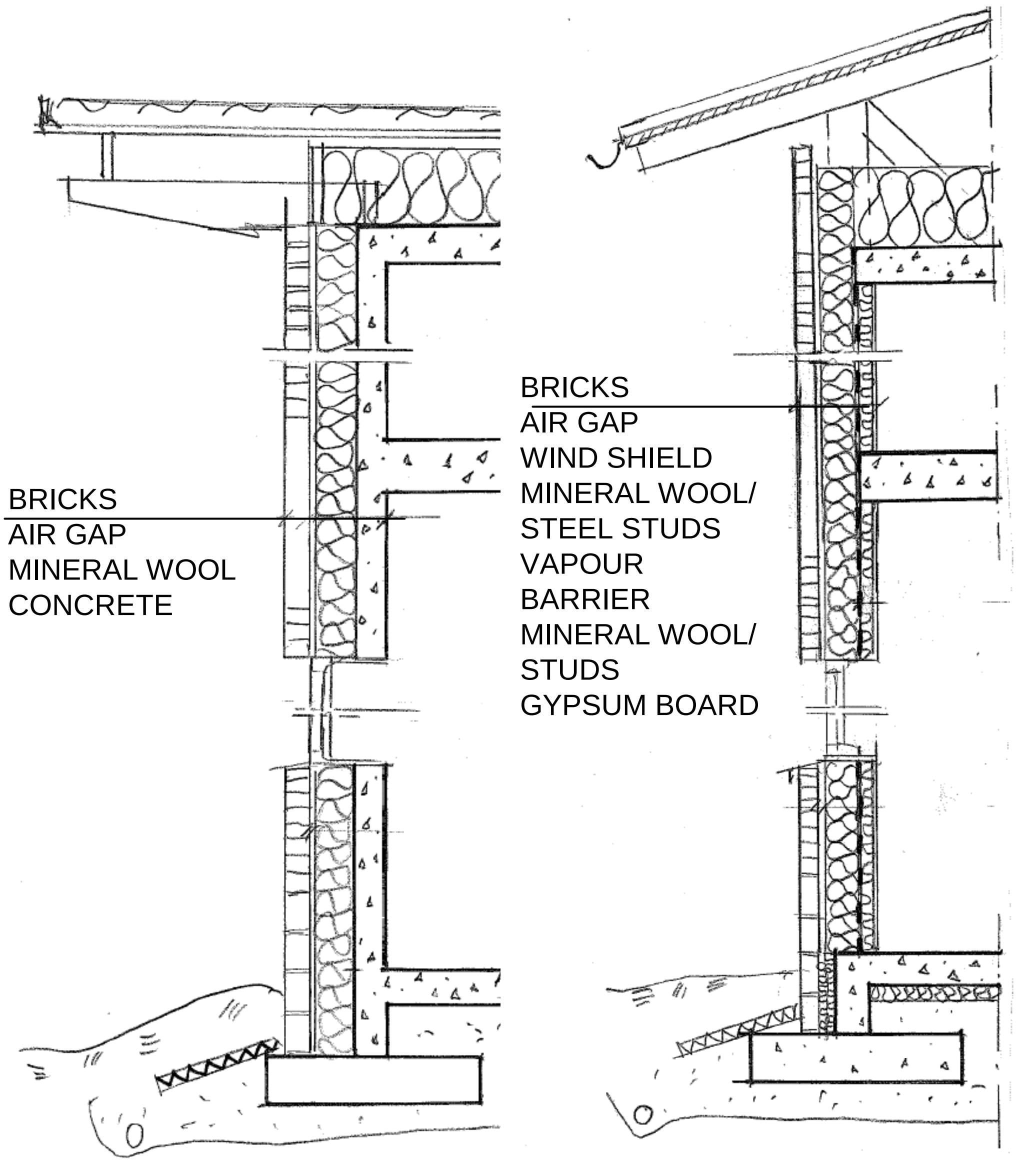
Table 5.H.2 Results of comparative calculations

Climate	Programme	Orientation of windows	Energy use for heating/cooling kWh/m^2,year	
			Solid	Light
Stockholm	Consolis	E/W	66,7	70,7
Stockholm	Consolis	S	51,5	56,5
Stockholm	VIP+	E/W	64,5	66,9
Stockholm	VIP+	S	54,5	60,1
Kiruna	Consolis	E/W	128,7	133,4
Malmö	Consolis	E/W	54,3	58,5
Toulon	Consolis	E/W	8	12,2

<u>Conclusions</u>

- There is good correlation for this type of calculation between the two tools. The largest difference 6,3% refers to the South-facing light weight alternative.
- The difference with regard to orientation of windows is more pronounced with the Consolis tool.
- The difference between solid and light is relatively independent on climate in real terms, but in relative terms the difference is larger in warmer climate.

ANNEX 6.A EXAMPLE OF WELL PROVEN DETAILING OF CONCRETE BUILDING – OUTER WALL SECTION



Typical load carrying concrete façade with brick cladding

Typical curtain wall façade with brick cladding

These two types of facades are often combined so that the load carrying concrete façade is applied for the gables while the curtain wall is used on the long sides, cf. Annex 4.A.1

ANNEX 6.B SUMMARY OF ADDED CONSTRUCTION COSTS FOR ALTERNATIVES BEST AND GOOD IN COMPARISON WITH NORM

Table 6.B.1 Added net construction costs for alternatives BEST and GOOD in relation to the NORM alternative. Calculations are based on cost data from June 2004 supplied by project management consulting company for application example 'H' in Chapter 6.

Part or system	Quantities	BEST Euro	GOOD Euro
Light interior walls inside flat instead of concrete walls, which are required for structural reasons in alternative NORM.	461 m^2	-3445	-3445
Added insulation in roof. 200/100 mm	416 m^2	2286	1143
Added insulation in walls. 150/40 mm	977 m^2	32209	8589
Added concrete* in floors	250/150 m^3	88791	55772
Added concrete* in walls	63/47 m^3	21530	16147
Improved windows. U-values see Table 6.7	240 units	26374	13187
Balanced ventilation with heat recovery	22 units	38681	38681
Sum		**2084898**	**1313754**

**Including reinforcement*

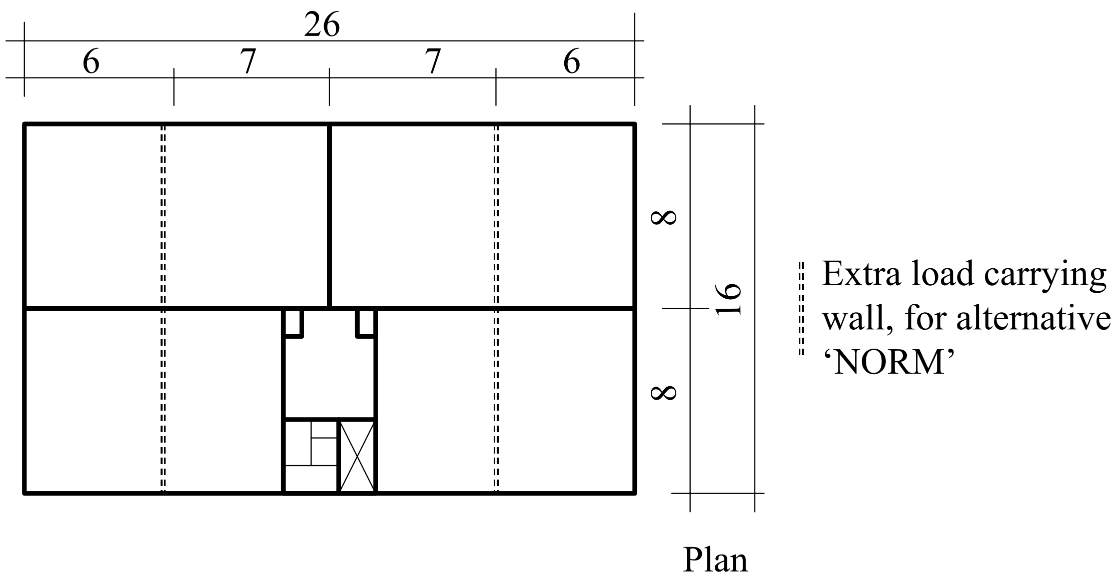


Figure 7.B.1 Structural outline

ANNEX 6.C SUMMARY TABLE OF LCC COMPUTATION (CASE 'NORM'

Life cycle cost and environmental load. Summary sheet

Project:	Lund NORM	Area (m2)	
Time horizon (years):	100	2400	Exchange rate €
Functional unit:	Entire building		9,1
Number of flats:	22		
Real interest rate (%):	3,0		
(or expected rate of return inflation			

		ANNUAL COSTS		NET PRESENT VALUE		
	Pricechange rel inflation (%)	Entire building (€)	€ per m2	Entire building (€)	€ per m2	Share (%)
Administration	0,50	15033	6	550419	229	6,4
Caretaking	0,50	16879	7	618014	258	7,1
Water and sewage	0,50	11341	5	585458	244	6,8
Electricity	1,50	3956	2	204230	85	2,4
Waste disposal	1,50	3640	2	133259	56	1,5
Heating	1,50	12185	5	629027	262	7,3
Insurance	0,50	1319	1	48282	20	0,6
Other annual cost	0,50	5011	2	183473	76	2,1
Periodic maintenance	0,50	22484	9	823239	343	9,5
Initial cost (production)	0,50	136860	57	5010989	2088	57,9
Property tax	0,00	9231	4	291682	122	3,4
Value or cost at end of life	0,50	-11585	-5	-424167	-177	-4,9
Sum		226352	94	8653905	3606	

	Socio economy according to: EPS 200				
Environmental discount rate (%): 0	Exchange rate € 1				
Environmental assessment	ANNUAL		TOTAL LIFE CYCLE		
	Entire building (€)	€ per m2	Entire building (€)	€ per m2	Share (%)
Production	1222	1	122185	51	13,1
Operation	9348	4	934791	389	88,4
End of life cycle	0	0	0	0	0,0
Sum	10570	4	1056976	440	

	kWh/m2
Annual energy use for heating including hot water	77

ANNEX 6.D SERVICE LIFE AND DURABILITY DESIGN OF CONCRETE. APPLICATION ON BALCONY SLABS

The balcony slab is exposed to carbonation, saturation and frost on the upper side, which refer to exposure classes XC 4 and XF 3 according to EN 206.
On the bottom side it is exposed to frost an air humidity but not saturation as it is protected from rain, which refer to exposure classes XC 3 and XF 1.
With regard to carbonation the standard requires a maximum water to cement ration of 0,55. In this case a grade C 40/50 concrete with water to cement ration 0,50 is selected.
The life spans considered are 60, 120 or 180 years. According to SBF (1998) the following formula can be utilised to determine the characteristic carbonation depth,T_1, at a specific time, t_1, if the carbonation depth, T_2, at the time t_2 is known.

$$T_1 = T_2 \times (t_1/t_2)^{1/2}$$

According to Tuutti (1982) the carbonation depth for a rain-protected concrete structure such as the bottom side of a slab is 20 mm at 50 years of age and the for upper side which is exposed to rain water the carbonation depth is 8 mm.

SBF (1998) recommends that the reinforcement cover should be the characteristic carbonation depth increased with one standard deviation, which can be set to 5 mm in this case.

The resulting theoretical concrete cover is thus

Design life	60 years	120 years	180 years
Upper side	14 mm	17 mm	20 mm
Bottom side	27 mm	36 mm	43 mm

The total cover including top and bottom side of slab is thus 41/53/63 mm for 60/120/180 years respectively.

Applying the Swedish standard for cover of reinforcement cover (SIS, 2002) the cover with water cement ratio of maximum 0,50 the cover should be for:
50 years: 20 + 10 = 30 mm,
100 years: 30 + 10 = 40 mm
Where 10 mm is the standard tolerance for house construction.

With regard to frost resistance, XF, the same concrete type is used in the entire slab so XF 3 governs the design. XF 3 requires entrained air pores to a total of approximately 5% percent by volume.

ANNEX 7.A CASE A. QUANTITATIVE LIFE CYCLE APPRAISAL. INPUT DATA AND RESULTS

Reference: Öberg, M. (2003-A) *Project A Livscykelberäkningar.* (Life cycle appraisal of project C). Internal report for the project team on application example A. 03-01-30. Division of Building Materials, Lund University, Lund, Sweden (in Swedish)

Alternative A1 = F I/Vent I, A2 = F I/Vent II, B1 = F II/Vent I, B2 = F II/Vent II. (C additional alternative for reference: Precast concrete with facade of sandwich elements)

Areas and volumes

Table 7.A.1 Areas and volumes for one building.

	BOA	BTA	BRA	Floor height	NTV
	m^2	m^2	m^2	m	m^3
Basement	0,0	388,1	356,4	2,4	855
Floor 1	299,0	384,0	343,2	2,52	865
Floor 2-6	315,5	384,0	343,2	2,52	
x 5	1577,5	1919,9	1716,1	12,6	4325
Floor 7	179,5	219,5	210,8	2,5	527
Sum 1-7	2056,0	2523,4	2270,1		5717
Total	2056,0	2911,5	2626,4		6572

BOA: Net floor area according to contractor
BTA: Gross floor area according to contractor
BRA: Usable floor area. Estimated from drawings
NTV: Net volume. Estimated from drawings

Other data

Real interest rate: 3%.
Price increase after inflation: 0,5%, except for environmentally related: 1,5% (heating, electricity and waste disposal). Reference: SCB (1999), Table 9.1.14: Development of costs in dwelling buildings in relation to consumer price index over 20 years.
Calculation horizon: 60 years.
Value at end of life: 50% of new production.
Annual rent: (To calculate loss of rent) 90 Euro/m^2, within flats (BOA), 45 Euro/m^2 in basement. (Subsidiary usable area)
Loss of area by FTX: 1 m^2/floor (BOA) for shafts + 30 m^2 in machine room.
Total project cost 3.838.000 Euro. Added cost for supply and exhaust ventilation with heat recovery (Vent II): 1700 Euro/flat, in comparison with mechanical exhaust ventilation (Vent I).

Brick curtain wall (F II): Production cost 27 Euro/m^2,wall area, lower than reference (F I).

Periodic maintenance for façades and ventilation systems relevant for comparison

Façades:

Reference: (F I) Lightweight concrete block-wall with water-protected surface. Outer surface: Thick rendering, painted with silicate colour. Inner surface: Thin rendering.

According to SABO (2001), for the general rendered façade, a 15% exchange is required after 30 years costing 23 Euro/m^2 and a full renovation after 60 years. In this case with thick rendering on masonry walls the 30-year repair is not deemed necessary. Instead a full renovation is planned after 50 according to (Sandin, 1995). The water-protected block surface implies that the rendering will be fully wetted by intense rain, as the elimination of moisture inwards through the blocks is blocked. This will require increased cleaning of the outer surface. However, as that is primarily an aesthetical effect it has not been taken into account by this calculation.

Alternative: (F II) Brick façade requires overhaul each 40 years costing 15 Euro/m^2 (Persson, 1999). Risk for frost damages on bricks not taken into account. It is assumed that frost resistant bricks are used.

Ventilating system:

Reference: Mechanical exhaust. (Vent I) According to SABO (2001) fan requires replacement after 22,5 years, costing 3490 Euro.

(Vent II) According to the ventilation sub-contractor the supply and exhaust system with heat recovery requires annual maintenance 880 Euro/building, in this case.

Table 7.A.2 Larger periodic maintenance items (Annual cost > 0,3Euro/m^2). Arranged according to cost

Component and activity	Interval Years	Number of units or area	Cost per unit Euro	Cost Euro	Annual cost Euro/m^2
Repaint flats	13	26	2506	65144	1,96
Sewage repair	45	26	5556	144444	0,74
White goods replace	13	26	594	15456	0,47
Windows replace	35	196	326	63852	0,42
Parquet flooring repl.	45	1605	39	62417	0,37

Table 7.A.3 Predicted life cycle cost for the reference alternative (F I/Vent I)

Cost item	Present value	Share	Annual cost	SCB (1999)*
	Euro/m^2	%	Euro/m^2	Euro/m^2
Production	1691	58,2	-54,7	50,6
Water and sewage	89	3,0	2,9	6,1
Waste disposal	42	1,4	1,1	
Common electricity	90	3,1	2,3	
Heating	293	10,1	7,4	6,3
Administration	115	4,0	3,8	9,9
Care taking	270	9,3	8,8	
Property tax	200	6,9	6,4	4,0
Insurance	10	0,4	0,3	0,3
Other annual cost	38	1,3	1,2	1,9
Periodic maintenance	260	8,9	8,4	6,2
Residual value**	-192	-6,6	-6,2	-
Sum	2905		-91,0	

** Statistical cost for the type of tenure and location*
*** Here a negative value indicates a positive residual value*

Energy balance calculations with the VIP+ programme

Table 7.A.4 Input data

Alter-native	Part of building	Type	Area	U-value	Air leakage by 50 Pa
			m^2	$W/m^2 {}^oC$	m^3/m^2,h
A	Facade North	F I Floor 1-6	271	0,32	2
A,B,C	Facade North	Light. Floor 7	43	0,23	3
A	Facade East/West	F I Pl 1-6	201	0,32	2
A,B,C	Facade East/West	Light. Floor 7	26	0,23	3
A	Facade South	F I Floor 1-6	246	0,32	2
A,B,C	Facade South	Light. Floor 7	38	0,23	3
B	Facades all	F II Floor 1-6	As A	0,23	3
C	Facades all	Concrete Floor 1-6	As A	0,23	1,5
A,B,C	Basement wall	Concrete	217	0,19	-
A,B,C	Windows N/E/S/W		122/80/153/80	1,32	2
A,B,C	Roof	Light	201	0,15	3
A,B,C	Roof	Terrace	158	0,17	1,5
A,B,C	Basement floor	Concrete	359	0,23	-
A,B,C	Interior wall base.	Concrete	223		
A,B,C	Interior wall	Lightweight aggr.	1128		
A,B,C	Interior wall	Light	1543		
A,B,C	Interior floors	Concrete	1582		

Indoor temperature: +22ºC during heating season. 'Free gains': El/persons 3,4/1,6 W/m^2 (in basement 0,7/0)

A1, B1, C1	Mechanical exhaust. Norm ventilation. 0,35 l/s
A2, B2, C3	Supply and exhaust with heat recovery. 70% utilisation factor. Supply air +20. Norm ventilation. 0,35 l/s

'South facade' 45 % angle to the South, Wind conditions: Medium open
Window glazing: 80%, transmittance 70%.

Table 7.A.5 Estimated energy balance. Average for climates 2000 and 2001

	Energy losses (kWh/m^2,year)					Energy supply (kWh/m^2,year)			
	Trans-mission	Air leaks	Ventilation	Hot tap water	Over-temperatures *	Solar gains	Other free gains	Heat recovery	**Bought energy**
A1	57,2	0,0	68,7	40,1	4,0	23,6	44,8		101,7
B1	53,9	0,0	68,9	40,1	4,4	23,6	44,8		99,0
C1	53,9	0,0	69,1	40,1	3,9	23,6	44,8		98,6
A2	57,6	3,5	69,2	40,1	3,9	23,6	44,8	30,8	76,5
B2	54,2	4,4	71,4	40,1	4,3	23,6	44,8	30,8	74,6
C2	54,3	3,1	69,6	40,1	3,8	23,6	44,8	30,5	73,6

** Theoretical cooling energy required when indoor temperatures reach a comfort level.*

ANNEX 7.B CASE B. QUANTITATIVE LIFE CYCLE APPRAISAL. INPUT DATA

Reference: Öberg, M. (2004-B) *Generationsvillan - Livscykelvärdering.* (Life cycle appraisal of project C). Internal report on application example B, for the block producer. 04-02-02. Division of Building Materials. Lund University, Lund, Sweden (in Swedish)

Areas and volumes

Table 7.B.1 Areas and volumes

	BRA	Floor height	Net volume
	m^2	m	m^3
Lower floor	124,8	2,5	312
Upper floor	126,5	2,8	354
Sum	251		666

BRA: Usable floor area. Estimated from drawings

Other data

Real interest rate: 3%.
Price increase after inflation: 0,5%, except for environmentally related: 1,5% (heating, electricity and waste disposal). Reference: SCB (1999), Table 9.1.14: Development of costs in dwelling buildings in relation to consumer price index over 20 years.
Calculation horizon: 60 years

Overview of structures and including maintenance data relevant for the comparison between the alternatives

Facades:

Reference: (S1) Massive lightweight aggregate concrete block-wall with 10 mm rendered outer surface painted with silicate colour and thin rendering on inside. Thickness: 400 mm. According to SABO (2001), for the general rendered façade, a 15% exchange is required after 30 years costing 23 Euro/m^2 and a full renovation after 60 years. According to the block producer this specific type of block and rendering a renovation is required after 40-45 years and the repair will the prolong the life span to a total of 60 years. These two alternative life plans converge reasonable.

Wood panel (S2) According to SABO (2001), the alternative wood panel façade require painting every 8,5 years costing 7,2 Euro/m^2 and replacement after 35 years costing 38 Euro/m^2 including painting.

The 'Isoblock' (S3) is a sandwich type block with outer and inner leaves of 100 mm lightweight aggregate concrete with 150 mm foam insulation in between. Surface treatment is identical with the massive blocks.

Ventilating systems:
Data on periodic maintenance according to SABO (2001). Energy performance according to energy balance calculation, cf. Tables 7.4 and 7.B.3.

Periodic maintenance

Table 7.B.2 Larger periodic maintenance items (Annual cost > 0,2Euro/m^2). Arranged according to cost.

Component and activity	Interval Years	Number of units or area	Cost per unit Euro	Cost Euro	Annual cost Euro/m^2
Repaint wood façade	8,5	154	7	1146	0,51
Replace wood façade*	35	154	38	5852	0,25
Façade total (S2)					0,76
Repaint flats	13	1	2506	2506	0,62
Heat recov. replace (V2)	22,5	1	1111**	555	0,13
Vent.fans repair (V2)	22,5	1+1	3490+2490	5980	0,70
Total vent (V 2)					0,83
Ventilation repair (V1)	22,5	1	3490	3490	0,41
Washing machines repl.	13	2	722	1444	0,36
Parquet polishing	20	231	12	2695	0,34
White goods, replace	13	2	594	1189	0,29
Windows, replace	35	16	326	5212	0,28
Roof felt, repair	27,5	127	19	2469	0,24
Water and sewage rep.	45	1	4800	4800	0,20
Stoves	17	2	510	1020	0,20
For comparison:					
Block façade rendering repair (S1, S3)	43	154	23	3593	0,16

* Including repaint
** Heat exchanger for single family application

Energy balance calculations with the VIP+ programme

Table 7.B.3 Input data

Alter-native	Part of building	Type	Area	U-value	Air leakage by 50 Pa
			m^2	$W/m^2{}^oC$	m^3/m^2,h
	Façade N	S1/S2/S3	55,9	0,37/0,21/0,19	1,5/3
	Façade O	"	43,6	0,37/0,21/0,19	1,5/3
	Façade S	"	10,3	0,37/0,21/0,19	1,5/3
	Façade V	"	44	0,37/0,21/0,19	1,5/3
All	Garage wall S		15,5	0,37	1,5
All	Wall against the ground S		15,5	0,37	1,5
All	Windows N		6,9	1,8	
All	Windows O		11,1	1,8	
All	Windows S		24,4	1,8	
All	Windows V		13,7	1,8	
All	Roof	Ecofiber	127	0,11	3
All	Door N			1	
All	Door O			1	
All	Slab on ground. Outer field	Leca, loose	48	0,28	-
All	Slab on ground. Inner field	Leca, loose	76,8	0,18	-
LECA/ Isoblock	Inner walls	LWAC	145		
Wood	Inner walls	Timber frame	145		
LECA/ Isoblock	Inner floors	LWAC	125		

Inner temperature: +22ºC during heating season. 'Free gains': Electricity/persons 5 W/m^2

V 1	Mechanical exhaust. Norm ventilation. 0,35 l/s
V 2	Supply and exhaust with heat recovery. 70% utilisation factor. Supply air +20. Norm ventilation. 0,35 l/s

Wind conditions: Medium open

Window glazing: 80%, transmittance 70%.

ANNEX 7.C CASE C. QUANTITATIVE LIFE CYCLE APPRAISAL. INPUT DATA AND RESULTS

Reference: Öberg, M. (2004-C) *Project C- Livscykelvärdering.* (Life cycle appraisal of project C). Internal report on application example C, for the client. 04-02-06. Division of Building Materials. Lund University, Lund, Sweden (in Swedish)

Areas and volumes

Table 7.C.1 Areas and volumes for one building

	BRA	ÖVA	Floor height	Net volume
	m^2	m^2	m	m^3
Lower floor	143	16	2,6	413
Upper floor	155	4	2,6	413
Sum	298	20		826

BRA: Usable floor area, ÖVA: Subsidiary usable area. Estimated from drawings

Other data

Real interest rate: 3%.

Price increase after inflation: 0,5%, except for environmentally related: 1,5% (heating, electricity and waste disposal). Reference: SCB (1999), Table 9.1.14: Development of costs in dwelling buildings in relation to consumer price index over 20 years.

Calculation horizon: 60 years

Production cost according to tender offers.

Sources of project data: Drawings and technical specification.

Periodic maintenance

Table 7.C.2 Larger periodic maintenance items (Annual cost > 0,3 Euro/m^2). Arranged according to cost

Component and activity	Interval Years	Number of units or area	Cost per unit Euro	Cost Euro	Annual cost Euro/m^2
Repaint flats	13	4	2506	10022	2,01
Sewage system rep.	45	4	5556	22222	0,77
White goods	13	4	594	2378	0,48
Parquet replace	45	281	39	10936	0,44
Roof sheet steel replace	42,5	180	67	12000	0,44
Windows, replace	35	30	326	3281	0,43
Parquet polish	17,5	281	12	3403	0,36
Exhaust vent fans	22,5	1	3490	3490	0,41
Supply vent fan	22,5	1	2490	2490	0,29
FTX	22,5	1	2630	2630	0,31

Energy balance calculations with the VIP+ programme

Table 7.C.3 Input data

Alter-native	Part of building	Type	Area	U-value	Air leakage by 50 Pa
			m^2	$W/m^2{}^oC$	m^3/m^2,h
OT,A1/ A2	Façade East	Light/Concr sandwich	60	0,13/0,21	2/1,5
OT/A1	Gables	Light/Concr	41	0,13	2/1,5
A2	Gables	Concrete Sandwich	41	0,13/0,21	2/1,5
OT,A1/ A2	Façade West	Light/Concr sandwich	65	0,13/0,21	2/1,5
All	Windows East		16,2/11,8	1/1,4	3
All	Windows in gables		2,7/1,7	1/1,4	3
All	Windows West		23,5/4,2	1/1,4	3
All	Roof		160	0,1/0,08	2/1,5
All	Doors East		5	1	3
All	Dörr gables		5,3	1	3
All	Slab on ground. Outer		51	0,21	-
All	Slab on ground. Inner		109	0,11	-
OT, A2 /A 1	Inner wall separating flats	Light/Concr	50		
OT, A2/ A 1	Inner wall	Light	303		
OT/A1, A2	Inner floor	Light/Concr	160		

Inner temperature: +22ºC during heating season. ’Free gains’: Electricity/persons 5 W/m^2

Mechanical exhaust. Norm ventilation. 0,35 l/s

Supply and exhaust with heat recovery. 60% utilisation factor. Supply air +18. Norm ventilation. 0,35 l/s

Wind conditions: Medium open

Window glazing: 80%, transmittance 70%.

Base for calculation of effect requirements according to Swedish standard

Table 7.C.4 Design outdoor temperature DUT_{20} is determined for alternative OT and A1 Swedish standard SS 02 43 10 (SS 1991).

Calculation of the required effect for space heating accordning to SS 024310

Transmission losses				*Ventilation and air leakage losses*	
OT and A1	Area	U-value	U x A	Heat cap. Air: [Wh/m^{3}ºC]	0,33
	m^2	W/m^{2}ºC	W/ºC	Air volume [m3]	666
Facades	206	0,13	18,4	**Ventilation**	
Windows	42	1,00	45,1	Air changes/hour	0,5
Door	17	1,00	21,8	Volume x ach x heat cap. air	109,9
Door 2	5	1,40	27,1	**Air leaks**	
Roof	160	0,10	16,0	Air changes/hour	0,1
Slab inner	109	0,11	12,0	Volume x ach x heat cap. air	22,0
Slab outer	51	0,21	10,8		
		Sum:	**151,1**	Sum: [W/ºC]	**131,9**

Calculation of heat apacity and time constant					
Alternative:	Area	Thickness	Density	Specific heat	Heat capacity
OT	m^2	m	kg/m^3	J/kg,ºC	J/ºC
Roof (light)	160	0,026	900	840	3144960
Facades (light)	206	0,026	900	840	4049136
Int. floor (light)	160	0,039	900	840	4717440
Slab (concrete)	160	0,15	2400	880	50688000
Parquet	320	0,022	500	2300	8096000
Int. walls (light)	353	0,039	900	840	10407852
Furnishings	320,6	0	8,33	2300	6144833
				Sum:	87248221
Time constant: [h]:			**86**	(Heat capacity/(Energy losses x 3600))	
=>Outdoor design temperature DUT_{20} |			**-17,3**	Climate zone:	Arlanda

Alternative:	Area	Thickness	Density	Specific heat	Heat capacity
A1	m^2	m	kg/m^3	J/kg,ºC	J/ºC
Roof (light)	160	0,2	900	840	24192000
Facades (light)	206	0,026	900	840	4049136
Int. floor (concre	160	0,27	2400	880	91238400
Slab (concrete)	160	0,15	2400	880	50688000
Parquet	320	0,022	500	2300	8096000
Int. walls (light)	303	0,039	900	840	8933652
Int. walls (concr	50	0,2	2400	880	105600000
Furnishings	320,6		8,33	2300	6142375
				Sum:	298939563
Time constant: [h]:			**293**	(Heat capacity/(Energy losses x 3600))	
=>Outdoor design temperature DUT_{20} |			**-12,5**	Climate zone:	Arlanda

The outdoor design temperature, $DUT_{20,}$ according to time constant and climate zone is tabled in the standard.
In case of heat recovery of exhaust air for preheating of intake ventilation air the ventilation loss component can be excluded. In this case the time constants would then be 140 h for OT, and 480 h for A1.

ANNEX 7.D CASE D. QUANTITATIVE LIFE CYCLE APPRAISAL. INPUT DATA AND RESULTS

Reference: Öberg, M. (2004-D) *Project D- Livscykelvärdering* (Life cycle appraisal of project D). Internal report on application example D, for the client. 04-04-14 Division of Building Materials. Lund University, Lund, Sweden (in Swedish)

Areas and volumes

Table 7.D.1 Areas and volumes

	Usable floor area	Floor height	Net volume	Number of flats
Floor	m^2	m	m^3	
0	492	2,5	1230	-
1	492	2,51	1237	6
2	492	2,51	1237	6
3	492	2,51	1237	6
4	240	2,5	599	3
Sum	1716		4310	21

Other data

Real interest rate: 3%.
Price increase after inflation: 0,5%, except for environmentally related: 1,5% (heating, electricity and waste disposal). Reference: SCB (1999), Table 9.1.14: Development of costs in dwelling buildings in relation to consumer price index over 20 years.
Calculation horizon: 60 years
Sources of project data: Drawings and technical specification.

Overview of structures and including maintenance data

Facades:
West: Curtain wall. Wood panel surface.
cording to SABO (2001), the alternative wood panel façade require painting every 8,5 years costing 7,2 Euro/m^2 and replacement after 35 years costing 38 Euro/m^2 including painting.
North, East, South: Curtain wall with surface of 15 mm rendering on insulation. According to SABO (2001), for the general rendered façade, a 15% exchange is required after 30 years costing 23 Euro/m^2 and a full renovation after 60 years.

A relatively large share of the façade consists of balconies build in by glass. SABO (2001) estimates a periodic repair costing 270 Euro/m^2 with 15 to 20 years interval.

Periodic maintenance

Table 7.D.2 Larger periodic maintenance items (Annual cost > 0,1 Euro/m²). Arranged according to cost

Component and activity	Interval Years	Number of units or area	Cost per unit Euro	Cost Euro	Annual cost Euro/m^2
Repaint flats	13	21	2867	60200	2,17
Renovation build in balcony	17,5	198	271	53570	1,36
Sewage system, repair	45	21	6189	129967	0,81
Windows, replace	35	132	733	96800	0,77
Parquet, polishing	17,5	1715	11	19056	0,48
Parquet, replace	45	1715	44	76222	0,48
Washing machine flats repl	12	21	542	11387	0,43
White goods	13,5	21	525	11025	0,39
Drying machine flats repl	12	21	358	7513	0,29
Elevators	30	1	30556	30556	0,28
Exhaust vent fans	22,5	2	3489	6978	0,12
Supply vent fan	22,5	2	2489	4978	0,08
FTX	22,5	2	3333	5267	0,09
Sum ventilation repair					0,29
Stove	17,5	21	500	10500	0,27
Roof sheet steel, replace	42,5	492	78	38267	0,26
Rendering, renovation	30/60	543	27/62		0,21
Exchange balcony*	~~50~~	~~15~~	~~2444~~	~~36667~~	~~0,20~~
Ventilation inspection	3	1715	1	953	0,18
District heating central	30	1	18667	18667	0,17
Services control system	10	1	3222	3222	0,16
Wood panel repaint/replace	8,5/35	171	8/30		0,13
Kitchen furnishings replace	35	21	800	16800	0,13
Roof steel details, replace	27,5	492	17	8200	0,12
Bathrooms, reonvation	32,5	21	661	13883	0,12
Staircase, repaint (4 floors)	15	1	3956	3956	0,11

For build in balconies service life > 60 years

Energy balance calculations with the VIP+ programme

Table 7.D.3 Input data

Entire building: 'E', Top floor flat: 'F'

Alter-native	Part of building	Type	Area	U-value	Air leakage by 50 Pa
			m^2	W/m^2ºC	m^3/m^2,h
E	Façade E	Wood pan.	6	0,20	3
		Rendering	259	0,17	3
F	Façade E	Rendering	22,8	0,17	3
E	Façade S,N	Rendering	142	0,17	3
F	Façade S	Rendering	11,9	0,17	1,5
E	Façade W	Window	165	0,20	1,5
F	Façade W	Rendering	12,4	0,17	1,5
E	Balcony, E/S/W/N	Glass	30/48/72/48	1,4	3
E	Window E/S/W/N	Glass	33/20/91/20	1	3
F	Window E/S/W	Glass	1,2/6,4/6,6	0,18	3
E/F	Roof	Light	492/72	0,18	3
E	Slab on ground, out		51	0,21	-
E	Interior wall	Concrete	264/535		
E/F	Interior wall	Light	1752/120		
E/F	Interior floor	Concrete	1223/72		
Basement					
E	Interior wall	Concrete	50		
E	Interior wall	Light	50		
E	Wall above ground		121	0,23	
E	Wall below ground		127	0,39	-
E	Slab on ground, in.		100/392	0,19/0,09	-
Inner temperature: +22ºC during heating season. 'Free gains': Electricity/persons 5 W/m^2 Basement: +15ºC. 'Free gains': Electricity/persons 2 W/m^2					
Supply and exhaust with heat recovery. 60% utilisation factor. Supply air +18. Norm ventilation. 0,35 l/s					
Wind conditions: Medium open Window glazing: 80%, transmittance 70%.					

ANNEX 7.E CASE E. QUANTITATIVE LIFE CYCLE APPRAISAL. INPUT DATA AND RESULTS

Reference: Öberg, M. (2004-E) *Project E- Livscykelvärdering* (Life cycle appraisal of project E) Internal report on application example E, for the contractor and element producer. 04-03-26 Division of Building Materials. Lund University, Lund, Sweden (in Swedish)

Areas and volumes

Table 7.E.1 Areas and volumes

	Usable floor area	Floor height	Net volume
Floor	m^2	m	m^3
Ground	176	2,78	489
1-3	176	2,48	436
Sum	704		1799

Other data

Real interest rate: 3%.
Price increase after inflation: 0,5%, except for environmentally related: 1,5% (heating, electricity and waste disposal). Reference: SCB (1999), Table 9.1.14: Development of costs in dwelling buildings in relation to consumer price index over 20 years.
Calculation horizon: 60 years
Sources of project data: Drawings and technical specification.

Periodic maintenance

Table 7.E.2 Larger periodic maintenance items (Annual cost > 0,1 Euro/m^2). Arranged according to cost. (Repaint of flats undertaken by residents)

Component and activity	Interval Years	Number of units or area	Cost per unit Euro	Cost Euro	Annual cost Euro/m^2
Sewage system repair	45	12	5556	66667	0,79
White goods	13	12	594	7133	0,62
Stove	15	12	510	6120	0,42
Rendering, renovation	30	377	27	10053	0,33
Windows, replace	35	48	326	15637	0,30
Elevators, replace	30	0,5	27222	13611	0,30
Balcony, replace	50	9	2444	22000	0,29
Roof, sheet steel, replace	42	200	78	15556	0,26
Ventilation inspect	3	704	1	391	0,18
Staircase, repaint (4 floors)	15	0,5	3956	1978	0,15
Ventilation fans	22,5	1	3489	3489	0,14
District heating central	30	0,33	16667	5556	0,12

ANNEX 7.F CASE E AND F. ENERGY BALANCE CALCULATIONS INPUT DATA AND RESULTS

Reference: Öberg, M. (2004-F) *FW- vägg element- Livscykelvärdering* (Life cycle appraisal of FW –wall element) Internal report on application example F, for the element producer. 04-05-18 Division of Building Materials. Lund University, Lund, Sweden (in Swedish)

Energy balance calculations with the VIP+ programme

Table 7.F.3 Input data

Part of building	Type	Area	U-value	Air leakage by 50 Pa
		m^2	$W/m^{2o}C$	m^3/m^2,h
Facades – long sides	Reference*/FW**	279	0,21/ varying**	3/2
Gables	Concrete+mineral wool +rendering	98	0,26	2
Windows		160	1,5	3
Door		25	1,4	3
Slab on ground, outer		41	0,25	-
Slab on ground, inner		135	0,16	-
Roof	Concrete+insualtion	176	0,11	2
Inner wall	Concrete	450		
Inner wall	Light	399		
Inner floor	Concrete	528		
Inner temperature: +22ºC during heating season. 'Free gains': Electricity/persons 5 W/m^2				
Mechanical exhaust ventilation. Norm ventilation. 0,35 l/s				
Wind conditions: Medium open. Window glazing: 80%, transmittance 70%.				

** Reference:Traditional curtain wall with timber stud. Outer surface of rendering on insulation*

*** Wall element in Section 7.6. FW 100 U=0,23, FW 125 U=0,21, FW 150 U=0,19*

Table 7.F.2 Beräknad energibalans (kWh/m²)

	Energy losses (kWh/m^2,year)					Energy supply (kWh/m^2,year)			
Long side - facade	Trans-mission	Air leaks	Ventilation	Hot tap water	Over-temperatures *	Solar gains	Other free gains	Heat recovery	**Bought energy**
Reference	67,7	0,0	76,7	48,6	20,9	57,1	43,8	-	113,2
FW 100	68,7	0,0	76,7	48,6	20,9	57,1	0,0	43,8	114,1
FW 125	67,6	0,0	76,7	48,6	20,9	57,1	43,8	-	113,1
FW 150	66,8	0,0	76,7	48,6	20,9	57,1	43,8	-	112,3

ANNEX 7.G CASE H. LIFE CYCLE APPRAISAL - INPUT DATA

Öberg, M. (2004-H) *Projekt H - Exempel på livscykelprojektering i tidigt skede.* (Project H – Example on early design phase application of ILCD) Internal report on application example H, for the client. 04-05-16 Division of Building Materials, Lund University, Lund, Sweden (in Swedish)

Areas and volumes

Table 7.G.1 Areas and volumes

	Usable floor area	Floor height	Net volume	Flats
Floor	m^2	m	m^3	number
0 and 1	324	2,6	842	8
Sum	648		1684	16

Other data

Real interest rate: 3%.
Price increase after inflation: 0,5%, except for environmentally related: 1,5% (heating, electricity and waste disposal). Reference: SCB (1999), Table 9.1.14: Development of costs in dwelling buildings in relation to consumer price index over 20 years.
Calculation horizon: 60 years
Sources of project data: Architectural drawings.
Production cost according to project management company.

Energy balance calculations with the VIP+ programme

Table 7.G.3 Input data

Alternative	Part of building	Type	Area	U-value	Air leakage by 50 Pa
			m^2	$W/m^2 {}^oC$	m^3/m^2,h
LE/NEX,NEF	Façade E/W	Light	240/172	0,13/0,22	2
LE/NEX,NEF	Façade N/S	Concrete	30	0,13/0,22	2
LE/NEX,NEF	Windows E/S/W/N		33/20/91/20	1/1,4	3
All	Door E		17	1,4	3
LE/NEX,NEF	Roof	Light	324	0,10/0,12	2
All	Slab on ground, outer	Concrete	118	0,17	-
All	Slab on ground, inner	Concrete	213	0,13	-
All	Inner wall	Concrete	218		
All	Inner wall	Light	343		
All	Inner floor	Concrete	324		-

Inner temperature: +21ºC during heating season. 'Free gains': Electricity/persons 5 W/m^2

LE; NEX: Supply and exhaust with heat recovery. 80% utilisation factor. Supply air +18. Norm ventilation. 0,35 l/s (0,5 ach). Supply air min +18 during heating season.
NEF: Intermittent ventilation 0,1/0,5 ach.

Wind conditions: Medium open. Window glazing: 80%, transmittance 70%.

ANNEX 8.A. QUESTIONNAIRE ON LIFETIME CONSIDERATIONS IN THE CURRENT DESIGN PROCESS

The survey comprised the following questions and was undertaken by personal interviews.

1. Which are the most important requirements on the building?
    a. From the owners point of view.
    b. From the tenants point of view.

2. Emphasis by design on constructability in relation to functionality?

3. Does the type of tender affect the balance between short and long term requirements?

4. Emphasis by design on first users needs discussed in relation to generality?

5. What actors contributed most strongly to the decisions?

6. Feed back of information? Any active measures taken?

7. Consideration of environmental aspects?
    a. Drivers for environmental concern?
    b. If there are contradictions between environmental and economical aspects: How is that resolved? What governs prioritization?

8. What is the market value of possibility to address life cycle quality?

9. Is the introduction of life cycle aspects in design a question of access to methods or of interest from your client?

The interviews were conducted with the following participators in the different projects:
- The responsible person in the project team of project A, architect ('AA'), structural engineer ('AS'), HVAC engineer ('AH'), electrical engineer ('AE') and large construction company ('AC').
- The leca-block manufacturer in project B ('B').
- The client of projects C, D, I ('C'), a mid sized semi-public housing company.
- The precast wall manufacturer in project F ('F').
- The client in project G ('G') a large semi-public housing company.

Table 8.A.1 Survey on lifetime aspects in the current design process. Answers. Letter code indicates respondent according to above.

1	**Which are the most important requirements on the building?** Materials, function and environment for both owner and user. (AA) Interest in quality of the building structure is increasing for both owner and user. (AS)
a	**From the owners point of view** Robustness. (AA) Operating economy. (AC, AE, AH, AS) Short building process, simple-easy to understand systems and structures, low energy use. (B) Low maintenance with robust and well proven technology and minimized energy use with individual measurements.(C) Architecture, aesthetics, sustainability, good operating economy. (G)
b	**From the tenants point of view**. Usability, indoor climate. (AC) Sound insulation. (AS) Location, low rent, standard on technical equipment-kitchen, functional quality in falling order. (B) Comfort and functionality, low rent, security in the flat as well as neighborhood. (C) Life cycle aspects are not so interesting. (F) Location, often personally related patterns related to work and children, usability, visible standard, access to parking facility, security. (G)
2	**Emphasis by design on constructability in relation to functionality?** In this project these aspects could be combined. (AA, AS) Reasonable balance. Point blocks with 4 flats per staircase most economical. Sound insulation is one item that needs consideration in this regard. (AC) Detail design is governed by production aspects. (AH) By design and build contracts constructability is more prioritized and vice versa by general contracts. (B) Rational solutions are pursued by predesign. However, by realization other alternatives are often selected. Other factors apparently influence this such as which contractor or specific market situation at the time. (C) Own development projects managed by construction companies are more production oriented than projects developed by owners such as housing companies. (F) Constructability is important but we need to become better clients. We are working on a design standard template open to adjustments.(G)
3	**Does the type of tender affect the balance between short and long term requirements?** Crucial is to have conscious clients. Then it is possible to 'sell' good long-term alternatives. (AC) Design and build works well. General contract often more expensive. Modified (controlled) design and build contract appears successful to reach balance (AE)

	The most important difference from structural point of view is that the design needs to be more open for different solutions with regard to production in a general contract. (AS) No. (B) The difference between clients is probably larger with regard to this than the tender form. (AS) Yes, and new types of collaboration forms definitely are required. In the future the tender should be organized so that all parties can profit. Then the optimal project can be obtained. (G)
4	**Emphasis by design on first users needs discussed in relation to generality?** Changeability not so important in this project. Some internal walls can be rearranged. (AA) Empty channeling for future use is built in. Separate shafts for electricity would further improve future flexibility. (AE) Not discussed in this project. (AH, AS) The first user may select some surfaces and furnishings, sometimes at an extra charge. If demands are unique the tenant may be requested to take responsibility to restore when moving off. At pre-design solutions to simplify future periodic maintenance of service systems are looked for. LCC calculation however, seldom justifies added investments with regard to that. The type of tenure does not affect this. We have to specify what we want in either case. (C) Flexibility in use is no important issue today. Projects are developed specifically for specific segments such as students or +55. People move rather than change the building. (F) The needs of the first user must be in balance with our long-term ownership. Flexibility and generality are discussed but not directly addressed in the design. (G)
5	**What actors contribute most strongly to the decisions?** In this project primarily in collaboration between architect, structural design and contractor. The usability aspects are fully satisfied. Façade was determined by client/city plan.(AA) The contractor. (AC, AE, AH) When the largest construction companies are involved they tend to take the lead. (B) Only the one who pays contribute. (C) Façade: The architect; Structural frame and often installations: Construction company.(F) The client with appointed advisors. (G)
6	**Feed back of information? Any active measures taken?** Should be improved. (AA, AC) Seldom. (AH, AS) No. But we should really try to improve on this. I particular when new technical solutions are employed. (B)

	When the project has started there is little interest in other things than the operation. (C) Routines for feedback are being developed in a development project with some other companies. (G)
7	**Consideration of environmental aspects?** Certain clients are very interested. The present state of knowledge limits the decision making. (AE) Yes, always included.(G)
a	**Drivers for environmental concern?** Requirements on materials dominate over energy and water consumption (AC) Individual payment of electricity and hot water are important both with regard to savings and to fairness between households. Space heating is difficult in this regard (AC) Must be the client. (AS) Environment is interesting when economical benefits also are involved. In case of obvious risks environment is also taken seriously. (B) National environmental objectives are in principle the design objectives together with environmental legislation. However, in practice there are no sanctions yet so it is up to the client so far but building regulations are changing. (C)
b	**If there are contradictions between environmental and economical aspects: How is that resolved? What governs prioritization?** Often it is said that the energy requirements are too expensive to fulfill. That should not be negotiable – then there is no conflict! (C) Environment may be decisive if economy is equivalent. Otherwise economy rules. (F) Environment prioritized but we cannot always afford the more expensive solutions (Exception: energy-related). (G)
8	**What is the market value of possibility to address life cycle quality?** No, architectural work is complex enough – this should be a special field of expertise. (AA) Yes. (AC, AE, AS) Yes, we can perform LCC analyses by system design. (AH) The tenants have little knowledge about these issues. (C) To day no but with a reformed rental legislation longer contracts with tenants could be achieved. (G)
9	**Is the introduction of life cycle aspects in design a question of access to methods or of interest from your client?** Both - Awareness, information and accessibility are important. (AA) Both. (AC, AE) Interest of client (AH) Methods are required. (AS) It is difficult to achieve interest for this. However, we should put it on the

	agenda. Clients need education. (B) To little time and knowledge for life cycle thinking in projects. Note that more expensive solutions directly effect the rent and the pay off time is often long. (C) Type of client. A long-term housing company is generally interested and furthermore well aware of what they want while the construction company is not so interested. (F) In a few years life cycle appraisal will be conducted in parallel to the current way of calculating projects. (G)
	Any additional remarks Ventilation is normally rudimentarily treated in dwelling buildings resulting in simple systems based on minimum requirements. It should be of interest to look at more sophisticated systems to obtain better indoor climate and energy performance. Heating system was in this project designed according to precise estimation of the required effect. (AH) To much emphasis is put on a fast process. Many mistakes are repeated. (B) A general contract requires prescriptive rather than functional objectives. Also because the evaluation of tenders then is easier. A design and build contract also requires well-defined design objectives. If these objectives are not marked as negotiable there are seldom any choices. A larger client organization should lead to more general contracts. (C) The optimal building has - very low energy requirements, - good comfort, no cold draughts, fresh air, is quiet and has good daylight, - freedom to choose equipment and furnishings. - rational periodic maintenance of systems, furnishings and surfaces, - ‘detached house’ feeling. Also some outdoor area that ‘belongs’ to the tenant, - create a good common atmosphere to avoid vandalism and - safe environment with regard to criminality. (C)