KUNGL TEKNISKA HÖGSKOLAN

Environmental Assessment of Materials, Components and Buildings

Building Specific Considerations, Open-loop Recycling, Variations in Assessment Results and the Usage Phase of Buildings

Mathias Borg
Doctoral Thesis

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Abstract

The building sector is a major contributor to the environmental loads generated by the society. The recognition of this fact by the sector and a general strive toward a sustainable society have lead to a focus on different tools that can be used to enhance the environmental performance of the sector and the society. Life Cycle Assessment (LCA) is one of these tools. The LCA methodology was initially developed for assessments of short-lived consumer products. The increasing interest in using the LCA methodology in the context of the building sector has initiated a development of the methodology to be able to consider the specific characteristics and considerations of the building sector. These are specific for the building sector, but not always unique. Examples of characteristics and considerations are: the long service lives of buildings, that each building is unique, the functional output is not always a physical product but rather a service. These have implications on several elements in the LCA methodology. The influenced elements that are dealt with in this thesis are in particular the modeling of the system, the functional unit, boundary setting, life cycle scenarios, scenarios and inventory of the usage phase and allocation procedures.

Buildings and constructions are commonly not static systems. The systems are rather dynamic in the sense that the system will provide different services based on the same physical structure during its service life. To be able to model the dynamic system, sequential life cycle thinking is introduced and a list of topics is derived. The list of topics is a structured presentation of issues that are of interest in the pursuit of a flexible LCA methodology. The goal is to find out if a methodological approach is suitable for modeling dynamic systems with a functional unit that is based on the provided service rather than the physical building.

Boundary setting, life cycle scenarios, allocation procedures, predicted service life and the modelling of the usage phase are all elements of the LCA methodology that have a potential to influence the result of an LCA in a significant way. The potential influence has been monitored based on the results of three case studies, which have been elaborated further to be able to estimate the magnitude of the potential influence.

There is a multitude of available allocation procedures presented and used in different contexts. The procedures are developed based on different considerations and with different intended applications. Two alternative allocation procedures are presented in this thesis. The first is a procedure developed with multi recyclable materials in mind and it is based on the recyclability of materials and products. The second procedure is quite recently developed and it is based on a combination of economic parameters and recyclability.

The importance of the usage phase for buildings and constructions has previously been recognised. The main contributors to the environmental loads generated during the usage phase are energy use, maintenance and emissions from products. It is, however, not very common to consider the usage phase in assessments conducted on materials and components, even though it is stipulated in e.g. ISO 14025 that the whole life cycle should be considered. A proposal of a model to estimate the environmental loads is, therefore, presented.

Keywords

Life cycle assessment, Building materials and components, Buildings and constructions, Allocation, Result variation, Usage phase, Energy demand

Preface

This Doctoral thesis is the aggregated result of my research in the field of life cycle assessment (LCA) and other environmentally related topics, e.g. energy simulations of buildings, with a special focus on the building sector. The work was initially, and for a short period of time, performed at the Swedish Steel Construction Institute (SBI) and continued thereafter at the KTH (Kungliga Tekniska Högskolan) in Stockholm, where the main part of the work was executed.

My interests in the topic of environmental assessment in general and life cycle assessment within the context of the building industry in particular, arose during the work with my Master of Science thesis at the SBI in 1996-97. The Master of Science thesis dealt with LCA of three building materials; mineral wool, gypsum boards and external wall studs made of cold-rolled hot dip galvanised sheet steel, which was combined to perform an assessment of an infill wall (Borg, 1997). The most interesting part of the thesis was, however, not the results but rather the way in which I together with Johan Anderson at the SBI had handled the allocation of environmental loads associated with multi-recyclable materials as steel. This method for allocation was later extracted from the Master of Science thesis and further elaborated and finally resulted in a separate SBI report, which were my first staggering steps towards a doctoral degree.

The real pursuit of a doctoral degree in science began when Professor Kai Ödeen at KTH, department of building materials, offered me, in the beginning of 1997, the opportunity to be accepted as a PhD-student. I accepted the offer in September of 1997, which made it possible to continue my work on the topic of allocation in LCA within a stimulating research environment including, among others, the co-authors of the papers that constitute the foundation of this doctoral thesis Martin Erlandsson, Johan Norén, Jacob Paulsen and Wolfram Trinius. The PhD-studies have resulted in several publications, e.g. Paper I to VII, and a Licentiate of Engineering thesis published in 1999.

I am very grateful that Martin Erlandsson, Johan Norén, Jacob Paulsen, Wolfram Trinius and Per Jernberg together with Johan Anderson (former SBI) and Joakim Widman (SBI), during the past four years have supported me in my work with fruitful discussions and useful comments. I do also want to thank Professor Kai Ödeen and especially associated Professor Ove Söderström for the opportunity, their critical review of my papers and their guidance in the labyrinths of science and research.

Further, I want to thank those of my co-workers at the department of building sciences that are not mentioned above, for the pleasure to have had the opportunity to make their acquaintance and for giving informal discussions and information exchange.

Stockholm, September 2001
Mathias Borg

List of Papers

This Doctoral thesis is based on the following papers:

I **Accounting for the High Recyclability of Steel in LCI and LCA Studies** *
Borg, M. & Anderson, J. (1998) Proceedings of the International Conference on Steel in Green Building Construction, Orlando, March 1998.

II **The Influence of Boundary Setting and Allocation Principles on the Results of LCA** *
Trinius, W. & Borg, M. (1998) Proceedings of the International Conference on Steel in Green Building Construction, Orlando, March 1998.

III **Influence of Allocation and Valuation on LCA Results** *
Trinius, W. & Borg, M. (1999) Published in the International Journal of Low Energy and Sustainable Buildings, Vol. 1 1999, Stockholm, April 1999.

IV **Proposal of a Method for Allocation in Building-Related Environmental LCA Based on Economic Parameters** **
Borg, M.; Paulsen, J.; Trinius, W. (2001) Published in the International Journal of LCA, Vol.6 No.4 2001, [http://dx.doi.org/10.1065/lca20001.04.051].

V **LCA as decision support in a product choice situation in the building sector – How to take the usage phase into account**
Paulsen, J. & Borg, M. (2000) Pre-print, Submitted for publication in the International Journal of LCA, December 2000.

VI **Energy Production Systems and Related Emissions**
Borg, M. & Norén, J (2001) Pre-print, Submitted for publication in the International Journal of Low Energy and Sustainable Buildings, March 2001.

VII **Generic LCA-methodology applicable for the construction and use of buildings – today's practice and needs for development**
Erlandsson, M. & Borg, M. (2001) Pre-print, Submitted for publication in Building and Environment, July 2001.

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* The articles are also included in the Licentiate of Engineering Thesis (Borg, 1999)
** The article is a modified version of an article included in the Licentiate of Engineering Thesis (Borg, 1999)

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1. Introduction

1.1 The Building Sector and The Environment

During the last two or three decades there has been a gradually increasing interest for the environment and the impact that human activity and actions have on the environment. This impact has been increasing ever since the beginning of the industrial revolution in the eighteenth century but has accelerated considerably since the end of the Second World War. The problem was, however, not acknowledged in a larger scale before the end of the 1960s, when the impacts of the increasing pollution of the environment began to be reflected in the state of the environment. The early noticeable impacts on the environment were often due to emissions of toxic substances and the accumulation of these in the environment, which led to negative consequences for large populations of animals.

The second type of impacts, that gradually began to become obvious to the environmental experts and later to the public, were acidification and eutrophication effects, which are regional effects, and the impacts that these effects had on forests around the world. These effects originated mainly from the combustion of fossil fuels (emissions of SO_2 and NO_x). Further examples of these more diffuse impacts that were recognised during the 1970s and 1980s are the global effects of stratospheric ozone depletion, which was mainly due to the use of CFCs, and the greenhouse effect. The latter did also, to large extent, originate from the combustion of fossil fuels (emissions of CO_2, CFC, CH_4, etc). The concerns of society, however, were not focusing on the environmental consequences of energy use at that time, but rather on reducing the energy demand, especially of fossil fuels, due to the energy crisis in 1973, i.e. increasing costs.

The concerns of society regarding the state of the environment have, however, changed since then and lead to several international and national agreements and guidelines in the pursuit of sustainable development and a strive towards protection of the environment, for example The Brundtland report (UN, 1987), The Rio declaration (UN, 1992) and The Kyoto protocol (UN, 1997). Based on theses documents and other information regarding the state of the environment the focus of the Swedish society have also changed and the debate and the policies from the government are nowadays concentrated on the environmental loads and impacts that originate in human activities. Furthermore, the focus has also changed from the identification of potential environmental threats, e.g. the thirteen environmental threats presented by the Swedish environmental protection agency, that have been revised and some new issues have been included to form a list of fifteen environmental quality goals. These environmental quality goals were adopted by the Swedish parliament in 1999 (Swedish Parliament, 1999) and they are intended to be measurable to be able to make a benchmark on the status of the environment. The intention of the government is that the environmental quality goals should be attained with in one generation, i.e. by the year 2020.

The building sector is affected by the overarching goal of the Swedish government to minimise the societies impact on the environment. The reduction of the impacts of the building sector is intended to be achieved by sector specific goals (Boverket, 1999a), which are detailed measurable goals regarding mainly material and energy flows and indoor environment. These sector specific goals are to be fulfilled by the building sector to meat the overarching environmental quality goal “a good built environment” (Boverket, 1999b), which handles the whole built environment and not just requirements on the erection and operation of buildings. The building sector is one of the key sectors in the pursuit of a sustainable society, this because the sector is responsible for approximately 40% of the total energy use in Sweden and uses approximately 7,5 billion ton of building materials per year.

Due to the fact that the impacts on the environment direct, or indirect, originating from human activities in general and industry production and transportation in particular, a need for different methods for analysis of production and transportation systems arose in the 1960s and 1970s. One of the methodologies developed is Life Cycle Assessment (LCA), which initially in the 1960s was used for assessment of energy demand for chemical processes and industrial production systems. The LCA methodology was gradually developed for the inclusion of emissions originating in the assessed production systems and also to include waste flows.

It was not until the beginning of the 1990s that a broader interest for LCA began to emerge. This broader interest was mainly due to company's need of environmental information and data to supply to customers, environmental labelling organisations and governmental agencies. This resulted in a further development of the LCA methodology but in two directions. One direction was further refinement of the existing methodology and the other was towards simplified tools for company internal applications as product design, e.g. The EPS-method (Environmental Priority Strategies in Product Design) (Steen & Ryding, 1993). Development during the beginning of the 1990s may have been focusing on the demand of tools and methodologies for different levels of detail but they were all more or less focused on relatively short-lived consumer products and their specific characteristics. This shortcoming of the existing LCA methodology became clear, when the Swedish building industry in the middle of the 1990s began to realise that the public's concern of the environment could not be ignored. The building industry found that LCA, among several other qualitative and quantitative methodologies for environmental assessment, was an interesting and useful methodology, but the methodology was not in all parts optimised for the building sector.

A problem regarding the implementation of LCA in the building sector was the absence of available environmental information regarding building materials and buildings, especially for the usage phase of buildings. Examples of factors that are problematic to handle with today's LCA-methodology and that are specific for the building sector are:

- The time aspect, long service life, which has implications on energy and maintenance scenarios.
- Disparate lifetimes for different building materials included in the same system, i.e. the building, and for the same building materials but in different functions included in the same system, which has implications on service life and maintenance scenarios.
- The high potential for recycling and reuse of building materials, components and whole building frames in combination with long service life, which has implications on end of life scenarios and how to handle distribution of environmental loads between life cycles.

These factors and several others have a large influence on in particular the following phases of an LCA:

- Goal and scope definition
- Inventory analysis

The specific problems related to the implementation of the life cycle assessment methodology in the building sector and the rising interest for the methodology has lead to the initiation of several both national and international research programs and workgroups. An example of these kinds of co-ordinated research efforts within the field of LCA is the SETAC (Society of

Environmental Toxicology and Chemistry) Working Group "LCA in Building and Construction" (SETAC, 2001).

1.2 Goal of the Research

The overarching goal of my research within the Department of Building Sciences, division of building materials at KTH was to contribute to the development and adaptation of the LCA methodology to the specific characteristics of the building sector. The focus of the performed research, within the field of LCA and buildings and constructions, is the development of methods for allocation of environmental loads and development of methods and, to some extent, calculation and analysis of data to enable a better handling of the, for buildings, significant usage phase.

The development of allocation methods is based on the hypothesis that it is possible to design methods that, in a feasible way, can make an approximation of the situation in which the recycling takes place and take the characteristics of the assessed material or component into account. This may be achieved by the use of economic values of products and components in different stages of the life cycle in combination with a quantification of the loss of material during the same stages or by the use of mass losses alone. The advantage of economic value as a basis for allocation is that the economic value reflects several different characteristics of a material in one parameter, for example demand and upgrade ability which are parameters that usually are hard to quantify.

Development of methods for inclusion of the significant usage phase of buildings in LCA-studies of building materials and components is based on the hypothesis that it should be possible to produce data regarding maintenance of building materials and components based on information on the building level in the design phase. The goal is to enhance the possibility to make better material and component choices from an environmental point of view. Building materials and components can have differences in characteristics, even though they fulfil the same function, which can result in significant variations of the environmental loads associated with a building during its service life.

1.3 Goal of the Thesis

The goal of this Doctoral thesis is to elaborate the topic of LCA in general and LCA in the building sector in particular, with a special emphasis on allocation, result variations and the usage phase of buildings.

1.4 Disposition of the Thesis

The Doctoral thesis is divided into six main paragraphs (the Introduction is excluded):

2. Life Cycle Assessment
3. LCA in the Building Sector
4. Result Variation in LCA in the Building Sector
5. Allocation of Environmental Loads
6. The Usage Phase of Buildings
7. Conclusions and Discussion

Paragraph 2 briefly describes the basic concept of life cycle assessment and is based on current ISO standards and other relevant state-of-the-art literature. The paragraphs main focus is on giving an appropriate basic level of knowledge in the field of life cycle assessment. This will be achieved by presenting the four methodological steps in an LCA, i.e. Goal and Scope definition, Inventory Analysis, Impact Assessment and Result Interpretation.

Paragraph 3 presents building specific considerations that should be handled by the chosen LCA methodology when conducting a building sector related LCA, this part is based on **Paper V,** and a brief presentation of a selection of available methodological approaches. The goal is to present crucial parameters to consider when to chose an approach or procedure for environmental assessment in the building sector based on the findings of **Paper VII**.

Paragraph 4 is a compilation of the results of **Paper II, III** and the part of the results of **Paper VI** that can be related to the topic of result variations in LCA studies in general and Building related LCA-studies in particular. The goal is to show the importance of conscious choices when initialising an LCA and choosing scenarios for energy supply systems and calculation methods to establish the energy demand.

Paragraph 5 deals with allocation within the context of LCA, predominantly allocation in the case of recycling, i.e. open-loop recycling. The aim of the paragraph is to give the reader brief information regarding allocation in general and common allocation methods used in building sector related LCA studies. Furthermore, the findings made and presented in **Paper I & IV** and applicable parts of the results and the information gathered in **Paper VII,** are also presented.

Paragraph 6 presents issues to be dealt with and a proposal of a methodological approach to handle the usage phase of building materials and components. The goal is to show that it is possible to handle the usage phase of materials and components in a material choice situation in the design phase of buildings by including information about the building and the building context, which is available in the design phase. The paragraph is based on **Paper V**

Paragraph 7 briefly presents the main conclusions that have been derived during my work with research in the field of life cycle assessment in the building sector and which are presented in **Paper I to VII**. The paragraph also contains a discussion and a proposal of topics that could be the subject for further research.

2. Life Cycle Assessment

The purpose of this chapter is to give the reader a brief orientation in and the basic concepts of the life cycle assessment (LCA) methodology to enable a more giving reading of the succeeding paragraphs. The paragraph is structured according to the disposition of and mainly based on the ISO standards regarding life cycle assessment that are available to me at present, i.e. the below listed ISO standards and other relevant state of the art literature.

- ISO 14040:1997 ”Environmental Management - Life Cycle Assessment - Principles and Framework” (ISO, 1997)
- ISO 14041:1998 ”Environmental Management - Life Cycle Assessment - Goal and scope definitions and inventory analysis” (ISO, 1998)
- ISO 14042:2000 ”Environmental Management - Life Cycle Assessment - Life Cycle Impact assessment” (ISO, 2000a)
- ISO 14043.2000 “Environmental Management – Life Cycle Assessment – Life Cycle interpretation” (ISO, 2000b)

LCA is usually described as a study of a material’s or product’s total environmental impact from “cradle to grave”, i.e. a study of the total environmental impact resulting from the life cycle of a material or product. More comprehensive definitions of life cycle assessment can be found in the ISO 14040 standard (ISO, 1997), the SETAC guidelines of life cycle assessment “A Code of Practice” (Consoli et al., 1993) or the Nordic Guidelines on Life-Cycle Assessment (Lindfors et al., 1995). However, this paragraph is mainly based on the ISO standards because it is the most recent of the three publications mentioned above. The ISO definition of LCA reads as follows (ISO, 1997):

LCA is a technique for assessing the environmental aspects and potential impacts associated with a product, by

- *compiling an inventory of relevant inputs and outputs of a product system;*
- *evaluating the potential environmental impacts associated with those inputs and outputs;*
- *interpreting the results of the inventory analysis and impact assessment phases in relation to the objectives of the study.*

LCA studies the environmental aspects and potential impacts throughout a product’s life (i.e. cradle to grave) from raw material acquisition through production, use and disposal. The general categories of environmental impacts needing consideration include resource use, human health and ecological consequences.

The LCA methodology can be divided into four successive phases; goal and scope definition, inventory analysis, impact assessment and result interpretation, which are presented in Figure 2.1 and more thoroughly elaborated in the remainder of this paragraph.

The iterative nature of life cycle assessments is displayed in Figure 2.1 by the double arrow in-between the four phases. This iterative characteristic of life cycle assessment is due to the disposition of the LCA methodology in which assumptions about processes to include, initial boundaries, initial data quality requirements and so on, are later compared to the actual outcome of the study. If the outcome shows that for example some sub-processes contribute significantly more to the result than anticipated a revision of the boundaries, data quality requirements, the gathered data, etc., i.e. the scope of the study (see 2.1.2 below), could be advisable in an attempt to identify the cause. Another reason for a revision of assumptions made initially in the assessment is if additional information about the studied process is gathered during the assessment.

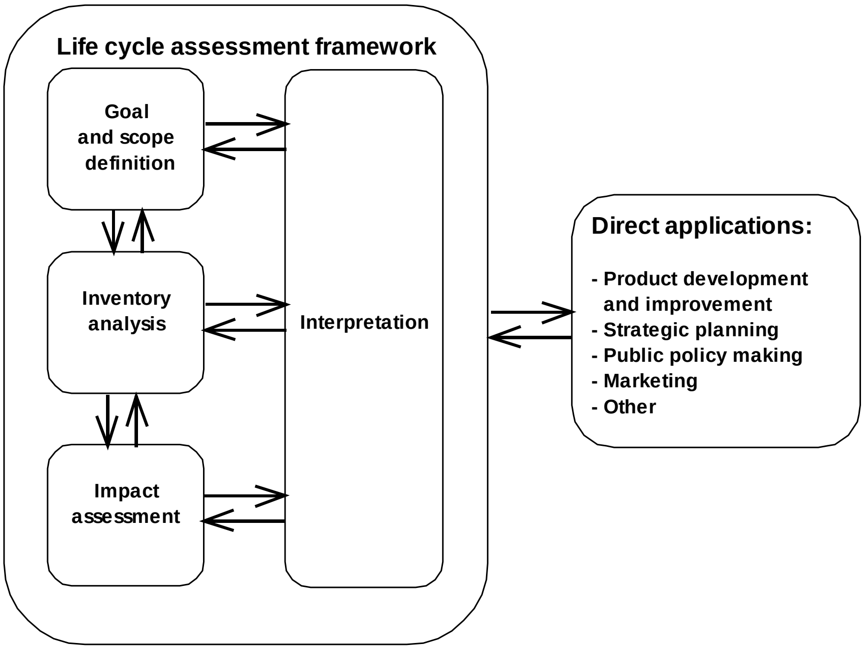

Figure 2.1 Phases of an LCA (ISO, 1997).

Life cycle assessments can be used in several different applications, e.g.: as support in decision-making, in product development, in identifying sub-processes that are major contributors to the overall environmental impact of the system (hot-spot identification), in comparisons between products with equivalent functions from a environmental perspective, in production of environmental product declarations.

2.1 Goal and Scope Definition

The goal and scope definition phase of an LCA is the first phase when conducting an LCA and the choices made within this phase will dictate the agenda for the assessment and have a major influence on the quality of the assessment results.

2.1.1 Goal of the Study

The goal of the study should be stated with outmost carefulness to avoid, as far as possible, misuse of the assessment results. Therefore, the goal of the study should clearly define the purpose of the study and the intended use and users of the results (Lindfors et al., 1995).

2.1.2 Scope of the Study

In the scope of the study it is important to identify and define the object of the study, what to include and what to exclude, the level of detail of the data in the study, etc, to be able to reach the goal of the study. The ISO 14040 standard has identified several items that should be considered, defined and clearly described in the scope of an LCA (ISO, 1997). The number of items has been reduced to those that can be considered crucial for the understanding of the extent and content of the scope in this presentation. These items are: the functional unit; the system to be studied; the system boundaries; allocation procedures; the types of impacts and the methodology of impact assessment and subsequent interpretation to be used; data requirement; assumptions; limitations; the type of critical review, if any. According to "the Nordic Guidelines on Life Cycle assessment" the goal and scope definition phase of an LCA should at least include decisions and definitions regarding (Lindfors et al., 1995):

- The purpose and intended application (see 2.1.1 above)
- The function of the studied system(s) and a defined functional unit
- The studied product group and chosen alternatives, if relevant
- The system boundaries applied
- Data quality needed
- A validation or critical review process

Based on the listing of items to include and to consider in the scope of the study presented in ISO 14040 and "the Nordic Guidelines on Life Cycle assessment", a number of items have been selected. These items are the functional unit, system boundaries, allocation procedures, data requirements (data categories and data quality requirements) and critical review and these are further described below.

Functional unit

The definition of the functional unit and the functional unit itself is of outmost importance when conducting a LCA and especially if it is a quantitative assessment, because the functional unit is the computational basis for the analysis, which all data will be related to. The functional unit will also be a well-defined and unambiguous measure of the function of the studied system and it will enable a verification that comparisons of different systems are made on a common basis. According to "the Nordic Guidelines on Life Cycle assessment" the functional unit of a product system must at least take the following aspects into consideration (Lindfors et al., 1995):

- The efficiency of the product
- The durability or the life spans of the product
- The performance quality standard

System boundaries

The definition of the system boundaries states which processes (unit processes) that will be included in the model of the assessed system. The system boundaries of a study must be consistent with the goal of the study and they ought to be motivated and presented in a transparent way to enable a critical examination. This mainly because the system boundaries have a major influence on the results of a LCA and as they are of subjective nature. The following system boundaries have been proposed to be considered and included in LCAs: Geographical, Life Cycle and Technosphere-Biosphere boundaries (Lindfors et al., 1995). The system boundaries and the interrelationship between the unit processes that constitute the modelled system may very well be presented by the use of a process flow diagram accompanied by supplementary technical information about the unit processes.

Allocation procedures

Allocation within the context of life cycle assessments denotes the partitioning of the environmental loads that arise within the studied system between products generated within the same production system or between succeeding life cycles. The allocation procedures that are to be used in the study should be presented and motivated in the scope of the study. The topic of allocation of environmental loads is further elaborated in 2.2.2 Calculation Procedures.

Data categories and data quality requirements

The goal of an LCA study dictates the data requirements for the assessment, i.e. which data categories that should be included, if the data should be site specific or generic and if it should be measured, calculated or estimated data. Examples of data categories that should be considered are (ISO, 1998):

- Inputs, e.g. energy, raw materials, ancillary materials, etc.
- Outputs, mostly products and co-products
- Emissions, e.g. to air, water and land (waste)

Furthermore, the scope definition of the study should include data quality requirements, which define the desired age, and the minimum time over which data should be collected, the geographic area from which data should be collected and the technology mix. The scope definition should also include quality requirement considerations regarding data precision, completeness, representativeness, consistency and reproducibility.

Critical review

A critical review is a methodological procedure that verifies whether an LCA study meets the requirements of the ISO standards regarding life cycle assessments or not. In the scope of the study it shall be defined if a critical review will be conducted and in the case that it will be conducted, it shall also be defined how and by whom.

2.2 Inventory Analysis

The inventory analysis is the second phase of an LCA and it consists of two main parts: data collection and calculation procedures. The main purpose of the inventory analysis is to collect relevant information about the unit processes that constitute the system under study for the data categories and in accordance to the defined quality requirements presented in the goal and scope phase. This information is then related to the functional unit and distributed according to the allocation procedures chosen in the goal and scope phase of the study. The results that have been derived within the inventory analysis phase are then presented either in tables or as histograms, “ecoprofiles”. If the LCA is terminated at this point in the conduction of the study in accordance with the goal and scope it is not a complete LCA. It is rather a Life Cycle Inventory analysis (LCI), which consequently is defined as an LCA where the impact assessment and result interpretation phases are omitted. The results from the inventory analysis that are later used in the life cycle impact assessment are usually denoted LCI results even though they are only sub-results.

2.2.1 Data Collection

The data collection usually concerns the gathering of information and data, either quantitative, qualitative or both, for each unit process concerning all relevant inputs and outputs regarding the energy and mass flows as well as emissions to air, water and land. Further information that should be gathered is information and data required for the allocation procedures and data for result variation and sensitivity analysis.

2.2.2 Calculation Procedures

There are several calculation procedures associated with the inventory analysis, which should be performed in the following order:

- Validation of data
- Relating data to the unit process
- Relating data to the functional unit
- Application of allocation procedure
- Aggregation of data

A validation of the data according to the data quality requirements established in the goal and scope phase should be conducted continuously during the data collection process. When an adequate amount of data has been collected, the data has to be related to each unit process. This is performed by determining a relevant reference flow to which the input and output data should be related. Thereafter, the input and output data for each unit process are interconnected according to the presented model of the complete system by normalising the flows of all unit processes in the system to the functional unit. The next step in the processing of the collected data is to apply the chosen allocation procedures to those unit processes that are multi-functional processes, i.e. produce more than one product, or contribute to more than one life cycle. The topic of allocation is further scrutinised in Paragraph 3 and 4. The final step in the inventory analysis is to aggregate the inputs and outputs of the studied system and presenting the aggregated data in tables or histograms.

2.3 Impact Assessment

The purpose of the Life Cycle Impact Assessment (LCIA) phase, the third phase in an LCA, is to make a probable estimation of the impact on the environment that is caused by the emissions emitted and resources used in the modelled system under study. The LCIA phase consists of three mandatory elements:

1. Selection and definition of impact categories
2. Assignment of LCI results (Classification)
3. Modelling category indicators (Characterisation)

The LCIA procedure gives, after aggregation, a category indicator result (LCIA profile). This result can be further elaborated by analysing the relative contribution of each category indicator to a reference value (Normalisation), grouping of results and weighting across impact categories. The final element in the LCIA presented in the ISO standard (ISO, 1998) is a data quality analysis element, which is optional in all applications but in comparative assertions. The structure of LCIA is also presented in Figure 2.2.

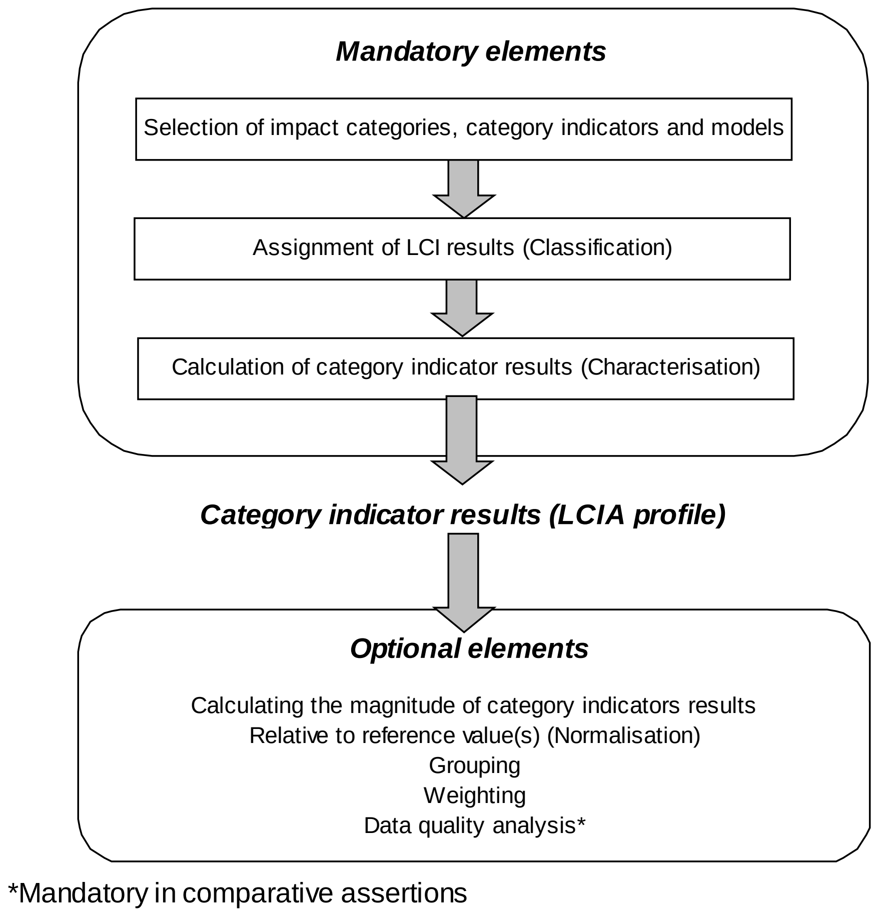

Figure 2.2 Elements of LCIA (ISO, 1998).

In this brief presentation the mandatory elements will be presented quite thoroughly while normalisation, grouping, weighting etc. will be dealt with in a perspicuous manner. Weighting in the ISO regarding LCIA is more or less the same element as the valuation step which was commonly included in earlier LCA guidelines, e.g. the SETAC "A Code of practice" (Consoli et al., 1993) and the Nordic Guidelines on Life-Cycle Assessment (Lindfors et al., 1995). The weighting element, weighting across impact categories, is according to the ISO 14042 standard not allowed in environmental assertions that are to be disclosed to the public (Udo de Haes & Jolliet., 1999a). This because the weighting can be, in part, based on value choices, subjective opinions, and not only assumptions, which are of a more technical nature and can in principle be empirically validated (Udo de Haes et al., 1999b). However, weighting is allowed in company internal applications as decision support etc.

2.3.1 Selection of Impact Categories, Category Indicators and models

The first element of the LCIA concerns the choice of impact categories, category indicators and models that will be considered and the choice shall be consistent with the goal and scope of the LCA study. The choice of **impact categories** to use for the visualisation of the impact on the environment, caused by the studied system, can be done between those that are commonly used or by defining new categories. Categories that could be considered are e.g.: global warming potential, acidification potential, eutrophication potential and ozone depletion potential. The second choice that is to be made is the choice of **category indicators** corresponding to the chosen impact categories. The category indicator is a quantifiable representation of an impact category (Udo de Haes et al., 1999b). CO_2 is e.g. a representation of the Global Warming Potential (GWP) category to which all relevant outputs in the LCI results contributing to GWP are related by the use of characterisation factors. The characterisation factors state the relative contribution of other relevant outputs to the chosen category indicator contributing to the same impact category. Selection of **models** concerns the choice of appropriate models for modelling e.g. systems to identify the reasons for global warming and deriving the appropriate category indicators for the current study. However, the data and information collected in the inventory analysis phase, and consequently the presented LCI result, might necessitate a redefinition of the goal and scope in this stage of the LCA, which once more emphasis the iterative nature of the LCA methodology. For example, it is stated in the goal and scope definition that the influence of the studied process on deforestation should be scrutinised and for that purpose the impact category eutrophication has been chosen, but there are no contributors to the impact category in the LCI results. Consequently, the goal and scope definition has to be redefined or a more thorough data collection has to be executed.

2.3.2 Classification

Classification is the procedure of assigning emissions, wastes and resources used and presented in the LCI results, to the impact categories chosen, e.g. CO_2, CH_4, CO will be assigned to the impact category GWP. The result of the Classification is a rearranged list of the content in the LCI result in which the data of the LCI concerning different environmental loads, e.g. emissions, wastes, energy use and resources is sorted under the different categories. An environmental load can contribute to more than one impact category and consequently that load will be double accounted. This is, however, not a problem as long as the categories do not contribute to the same cause-effect-chain.

2.3.3 Characterisation

The Characterisation step in the LCIA deals with giving an account of all the environmental loads associated with each impact category to the chosen category indicator for that impact category. This is done with the help of characterisation factors (equivalency factors (Wenzel et al. 1997)), e.g. the emissions of CH_4 and CO that contribute to the category GWP and will be converted into CO_2-equivalences. Finally, the converted LCI results are aggregated into a indicator result (ISO, 1998), which is the final result of the mandatory part of an LCIA.

2.3.4 Normalisation, Grouping, Weighting etc.

The indicator result can be further elaborated by:

- Normalisation, i.e. calculating the magnitude for each indicator result relative to a reference level(s)
- Grouping, i.e. sorting and/or ranking of impact categories based on e.g. if the categories deal with emissions or resources
- Weighting, i.e. ranking and usually aggregating the indicator results based on some value choice based numerical hierarchy, e.g. GWP is considered to be twice as important as ODP (Ozone Depletion Potential)

According to ISO 14040 data prior to weighting should always be available if weighting is applied to the indicator result.

2.3.5 Alternatives to LCIA According to ISO 14042

There are alternatives to the described LCIA procedure available. These alternative methods are usually based on the same structure as LCIA, but do not fully comply with the recommendations in the ISO-standard.

Impact assessment methods that were commonly used, and still are used to some extent, are methods where the steps of LCIA, according to ISO, are combined into one step, the valuation step. The problem with that kind of valuation methods is that they are more or less "Black Box-methods", which means that they usually are not as transparent as could be desired. They do, however, have several advantages e.g. easy to apply, repeatability and feasible. Examples of this type of valuation methods are the EPS-method (Environmental Priority Strategies in Product Design) (Steen & Ryding, 1993), the Ecological scarcity method (Ahbe et al., 1990) and the Environmental theme method (Heijungs et al., 1992). The latter two have been adapted to Swedish conditions by Baumann et al. (1993). These three methods are quite commonly used in Sweden for valuation of LCI results. They are usually used together, i.e. all the three aforementioned methods are used in the valuation because the use of three methods will give a broader base for the valuation as three sets of value choices by this can be incorporated. The use of at least three methods is proposed and recommended in the Nordic Guidelines on Life Cycle assessment (Lindfors et al., 1995), when valuation is conducted with this kind of methods.

A newly developed method that is closely related to the one step methods, is the BRE method presented in a methodology report regarding environmental profiles of construction materials, components and buildings (Howard et al., 1999). This method is based upon the work by CML (Centre of environmental Science, Leiden) (Heijungs et al., 1992) and the impact assessment result is presented in Ecopoints. These Ecopoints are calculated as population equivalents based on impacts from an average UK citizen and weighted according to an expert panel.

Another approach to impact assessment is represented by the Eco-indicator 99 method (Goedkoop & Spriensma, 1999), which is a damage oriented approach in contrast to the theme oriented methods represented by for example the Environmental theme method (Heijungs et al., 1992) developed by CML and the EDIP-method (Hauschild & Wenzel, 1998) developed by the Institute for Product Development in cooperation with the Technical university of Denmark, the Danish Environmental Protection Agency and several Danish industrial companies. Damage oriented assessment methods aim at presenting the damages caused by the loads presented in the LCI, e.g. damage on human health, ecosystems etc, while the theme oriented methods aim at aggregating the LCI-result into categories on which they can have potential effect, e.g. global warming potential, ozone depletion potential. Furthermore, the Eco-indicator 99 method is more or less congruent to the ISO-standard even though it is designed to deliver a weighted assessment result, which is optional in internal assertions but not allowed in assertions disclosed to the public, by offering the possibility to use a graphical presentation, "a mixing triangle", that depicts the outcome of a comparison for all possible weighting sets.

2.4 Result Interpretation

The content of the result interpretation phase of an LCA is dependent on the goal of the study; i.e. if the study is a comparative assertion, a recommendation based on the preceding phases of the LCA will probably be presented.

According to the ISO-standard on life cycle interpretation, ISO 14043, the life cycle interpretation phase of an LCA or LCI do consist of three elements (ISO, 2000b):

- Identification of significant issues
- Evaluation based completeness check, sensitivity check and consistency check
- Conclusions, recommendations and reporting

The first element, “identification of significant issues”, includes structuring the findings from the inventory analysis and results from the impact assessment phases together with information on data quality suitable way, e.g. based on the processes included in the study, and is usually presented in tables and histograms. Furthermore, available information regarding methodological choices, value- choices, interested parties and results from critical review process is also gathered and presented in a structured way for further analysis.

The aim of the second element is to establish and enhance the reliance in the results of the assessment by the use of e.g. methods for uncertainty and sensitivity analysis and the evaluation should be in compliance with the goal and scope of the study. Performing a sensitivity analysis may be very helpful in the understanding of the result and identification of major contributors to a specific result and especially interesting if the presented results differ considerably from other studies performed on the same kind of system, material or product because the difference may not only be assignable to the system under study, but also to the methodological choices made during the execution of the LCA.

The drawing of conclusions based on an LCA study should be an interactive procedure with the other elements of the interpretation phase. This means that preliminary conclusions should be drawn and then checked to ensure that they are in compliance with the goal and scope. If the conclusions are consistent, they should be presented with full transparency regarding value choices, expert judgements etc. otherwise return to the appropriate preceding element and derive a new preliminary conclusion, which in turn should be checked.

3. LCA in the Building Sector

The continuously rising concern for the environment amongst the public, governmental regulations and the aspiration towards a sustainable society has resulted in that the building sector has shown an increasing interest in different methods for environmental assessment of the activities of the sector. Examples of methods relevant for the building sector are LCA and Environmental Impact Assessment (EIA), which is aimed at assessing local and regional direct and indirect environmental effects of societal activities. The use of LCA in the building sector has initiated an adaptation of the LCA methodology to special conditions of the building sector and the efforts to adapt the methodology have resulted in several national and international methodology and tool development projects and working groups. Examples are the development of a methodology for environmental profiles of construction materials, components and buildings and the Envest design tool at the Building Reaserch Establishment (BRE) in the UK (BRE, 1999) (Howard, 1999) (Anderson, 2000) (Dickie, 2000), the development of the Eco-Quantum tool in the Netherlands (Makt, 1997) (Kortman, 1998), the BEAT 2000 tool in Denmark (Holleris Petersen, 2000), the ATHENA^{TM} tool (Trusty, 1997), the BEES tool (Lippiatt, 2000) and the Working group of SETAC-EUROPE on LCA in Building and Construction.

The building sector has initiated an adaptation of the LCA methodology to the specific characteristics of the sector. The efforts to adapt the LCA methodology originate in the awareness that the characteristics of the building sector are dissimilar to other industrial sectors. Another incentive for adaptation and development of the LCA methodology for the building sector is the fact that the building sector is a main contributor to the use of energy and various materials in society. The focus of these efforts is on adapting the LCA methodology to sector specific considerations that have to be addressed by the LCA methodology in order for the sector to be able to benefit from LCA to a full extent.

3.1 Building Specific Considerations

The execution of LCA-studies within the context of the building sector is faced with a number of sector specific considerations that have implications on the LCA methodology that is to be used in the assessments of buildings and constructions. Examples of considerations that are specific for the building sector, but not always unique, and problematic to handle with today's LCA-methodology are:

- Each building is unique and the degree of standardisation in the sector is at a minimum
- The function that products like buildings and constructions have, is not always easy to define strictly in compliance with ISO, i.e. the function is not always only of a technical nature, e.g. the building or the construction it self, but rather a service, e.g. housing
- It is not always possible to establish a functional unit in compliance with ISO for assessments of building materials and components, while a context usually is required to enable the set up of a functional unit for building materials and components.
- The time aspect, e.g. long service life compared to consumer products which has implications on energy and maintenance scenarios
- The long service life of buildings and constructions has as a consequence that a major part of the environmental load associated with a building or construction occurs during the usage phase
- Disparate lifetimes for different building materials included in the same system, i.e. the building, which has implications on service life and maintenance scenarios

- Disparate lifetimes for the same building materials but in different functions included in the same system, i.e. the building, which has implications on service life and maintenance scenarios
- The high potential for recycling and reuse of building materials, components and whole building frames in combination with long service life has implications on end of life scenarios and how to handle distribution of environmental loads between life cycles

These factors and several others have a large influence on the following elements of an LCA:
- Goal and scope definition – description of the studied system and functional unit
- Inventory analysis - boundary setting, life cycle scenarios and the choice of allocation method, especially in the case of recycling, and inventory of the usage phase of buildings

The factors presented above have implications on several other elements and phases of an LCA and a more comprehensive list over afflicted elements and procedures can be found in the SETAC-EUROPE report "LCA in Building and construction" (SETAC, 2001). The elements and procedures listed are a selection of topics that will be elaborated further in the remainder of this thesis.

3.2 Building Sector Imposed Requirements on LCA Methodology

LCA is used within the building sector on two superior system levels, assessment of building materials and components and assessment of buildings and constructions (SETAC, 2001). Assessments on the material and component level can be performed with two different purposes, either to generate input to whole building assessments, assessments on the building and construction level, or for product comparison, improvement and development. Assessments on the building level can for example be conducted to be a part of a decision support, either in the design phase of a building or construction or in the process of establishing the environmental status of existing buildings in the context of a purchase situation and extension or alteration situations. The first level, materials and components can be divided into three different levels: the raw material, the building material and the component level (**Paper V**), see Figure 3.1.

The boarder between the products on the three levels is not easy to define and a product can therefore be considered as a raw material in one case and as a building material in another. There are, however, at least two factors that unite the products of these three system levels:
- LCA for products on level 1-3 is often performed as part-LCAs to be added with other part-LCAs to form a LCA for a building or construction
- The products on level 1-3 cannot be assigned a functional unit in compliance with ISO 14040-43 due to the fact that they do not have a function until they are combined with other products and installed in a building or construction

These three system levels can, due to these similarities, be aggregated into one system level when LCA methodology is concerned. Building material and components together as an entity is in the SETAC-EUROPE report defined as Building Material and Component Combinations (BMCC).

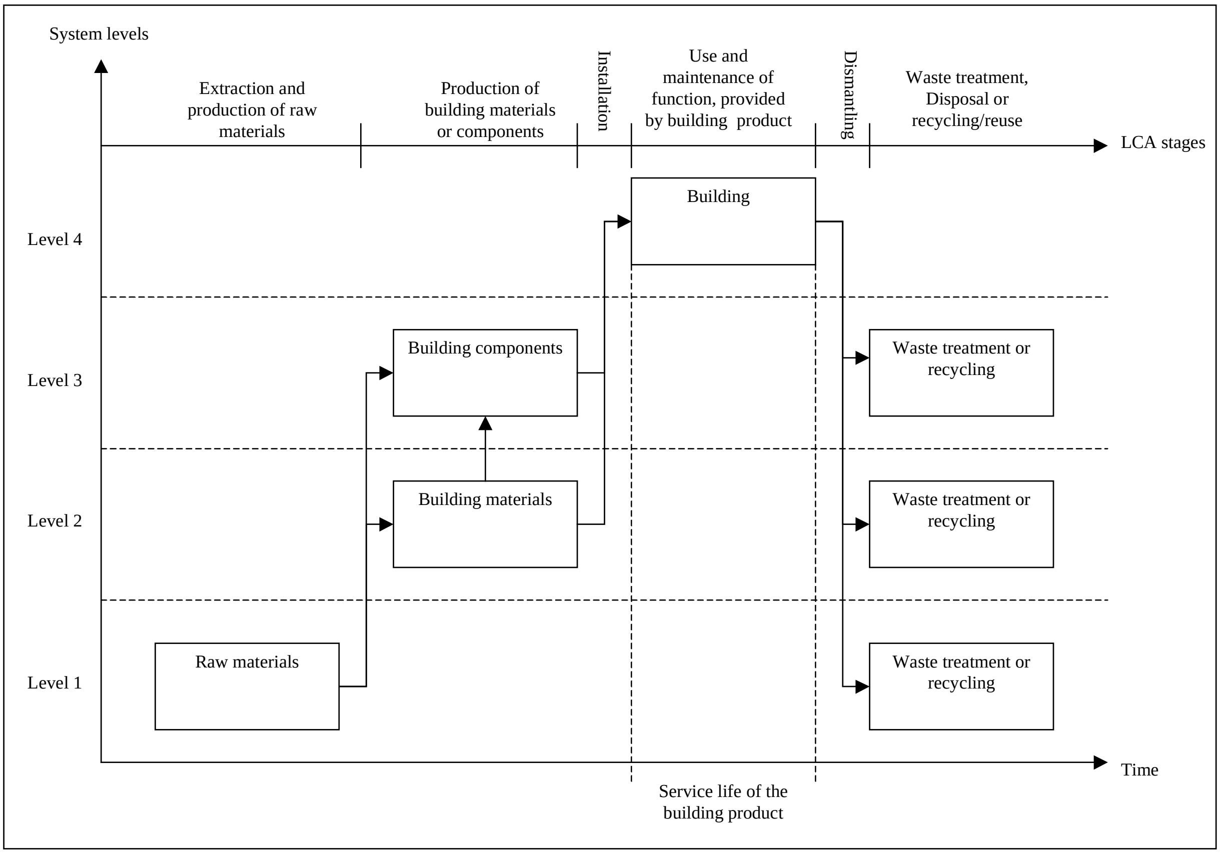

*Figure 3.1 System levels in a building products life cycle (**Paper V**).*

LCAs performed in the context of buildings and constructions are either performed on the building material and component level to derive information that will serve as decision support, e.g. in a material choice situation, or on the building level with the aim of further improvement. Assessments on the building material and component level are characterised as being performed with a bottom up approach while the building level assessments are conducted with a top down approach. The bottom up approach that are commonly used in the case of environmentally conscious material and component choice situations are, due to the nature of a bottom up approach, not utilised to handle the usage phase of the assessed entity in a sufficient way (see Paragraph 6). The bottom up approach is also quite common in methodologies for whole building assessments with the result that the whole building assessments usually suffer from the same incapacity to accurately assess the usage phase. The top down approach on the other hand is a better methodological approach when to assess whole buildings or the service that a building provides.

The problem with defining a functional unit is not only a problem that occurs in studies of BMCCs but also for studies of whole buildings and constructions. The problem in the latter case is not whether it is possible to define a functional unit or not, but rather a problem regarding how to define the function, i.e. is it the building itself as a physical object that is the function, e.g. m^2 residential floor area, or is it the service that is provided, e.g. housing. Another problem is to define how extensive the studied system should be, i.e. defining the system boundaries, both in spatial terms and in terms of the studied period of time.

The building sector of today strives towards converting the design process of buildings and constructions from having a focus on the physical building towards using performance requirements as the basis for design, i.e. the focus is to satisfy the need for certain services rather than providing a simple physical structure. This approach towards the definition of a building or construction has as a consequence that the assessed object is not a static system any more but rather a dynamic system that provides different services over time but it is probably based on almost the same physical structure. The approach of regarding the service rather than the physical building has implications on the modelling of the life cycle of the assessed building or construction as the linear life cycle is not valid for a dynamic context. What is required is a *sequential life cycle* thinking to be able to accurately model the life cycle. The sequential life cycle of a physical construction can be divided in different activities such as construction, maintenance, rebuilding, extension, operation and “end of life scenarios” e.g. including demolition and material recycling, while operation can more or less be regarded as a continuous process. The basis behind the sequential life cycle approach is that the different life cycle phases should be treated separately in the life cycle inventory analyses. Depending on the actual boundary conditions it is then possible to add up the sufficient life cycle phases corresponding to the goal and scope definition (**Paper VII**).

The primary system that are to be assessed can be divided into two subsystems with the purpose to make the modelling as flexible as possible. The first subsystem is the physical construction and the second subsystem is the building related operation. This division of the primary system is essential for two reasons:

- Performance requirements and building services can often be grouped in these two major issues. In an LCA it should be possible to consider the construction (consisting of building elements), building products and finally building and auxiliary materials (solvents etc) separately.
- The main part of the environmental impacts associated with the physical construction is often known while the characteristics of future operation usually are determined by assumptions. Normative scenarios can always be established for future events, at least for comparative assertions, while “known” potential impacts are not negotiable.

The second subsystem “building related operation” indicates that the activities that are to be included are activities that are influenced by the utilisation of the building or dependent on the building design, whereas other activities that are not influenced by the utilisation of the building or dependant on the building design, will not be considered.

Based on the perspective of assessing buildings and constructions with a basis in both the physical building and the service that the building or construction provides, rather than with a basis in the physical building only, the following topics, see Table 3.1, were identified to be of interest in the strive towards a flexible LCA methodology suitable for assessment of the provided service (**Paper VII**).

Decision supported by	Sub groups	Topics
Scope	Building life cycle phases and status	Definition of the buildings life cycle phases
		Assessment of a new building
		Assessment of a existing building
		Assessment of an activity, i.e. rebuilding, extension, demolition
	Services coverage	Water consumption and use
		Waste water system
		Heating and cooling system
		Ventilation system
		Building maintenance, i.e. durability aspects
		Plot operation and maintenance
		Building related choice vs. user related impact
	Time dependence (coverage)	Average of today’s practice
		Time dependence affecting LCI
		Time dependence affecting LCIA
Methodology	Inventory	Allocation procedure for processes
		Handling of material recycling (i.e. open-loop recycling, boundary setting between products)
		Sunk costs
		Scenario modelling
		Time dependence (i.e. data for future processes)
		Procedure obtaining specific or generic data
		Procedure for dealing with data gaps
	Impact assessment	Indoor air quality, IAQ
		Time dependence
		Spatial difference
		Geographical difference
		Impact categories
		Conservation of resources
		Valuation methods

*Table 3.1 Different topics used to characterise different LCA systems applicable for buildings (**Paper VII**).*

3.3 Building Sector Related LCA Methodologies and their characteristics

Based on the topics presented in Table 3.1 and the opinion that the service that the building is intended to supply should be considered, a study of five building related LCA methodologies, which are implemented in LCA tool, was performed. The purpose with the study, which is presented in **Paper VII**, was to find out if the topics above were handled by the five tools, to identify what the current practice in LCA tools for the building sector looks like and to identify areas of concern for future research, i.e. the purpose was not to analyse the tools with the intention of ranking the tools.

The five tools that were analysed were:

- ATHENA Sustainable Materials Institute, "ATHENA™"
- BRE, "Envest"
- IVAM, "Eco-Quantum 3"
- SBI, "BEAT 2000"
- US EPA, "BEES"

The five tools differ in intended utilisation and approach and they are designed to be used at different building levels. The difference is that the majority of the tools is developed based on a bottom up approach, i.e. a combination of building materials and components sums up to a building, even though they are designed to consider the whole building including energy demand etc. The only tool that is based on a top down approach is the Envest tool, which is a tool explicitly developed for use in the design phase of a building project. The BEES tool has a different approach compared to the other tools, while it is designed for decision support in material choice situations.

The five tools were studied by analysing available methodology reports and by sending the persons that are responsible for the respective tool a questionnaire. The results of the study that are of interest in the context of this thesis are:

- A general impression is that it is considered that supplying marginal, average and best available technology LCI data satisfies the intention to cover the time dependence of LCA studies of buildings. This can, however, be insufficient if there is no possibility to build scenarios, which consider technical development that can change the studied system and the context of the studied system over time.
- There is no consensus among the studied tools regarding how to handle allocation, both in the case of recycling and in the case of multi input and output processes. It seems, however, that the more recently developed or updated methods tend to base their allocation procedure on economic parameters.
- A majority of the tools do not allow the user to define the service life. They have instead built in predefined service lives of 50 to 75 years, depending on the tool.
- Due to the fact that majority of the tools is based on a bottom up approach they handle the usage phase by applying a material and component replacement rate based on the applied service life, either default or given by the user, and either standardised information regarding cleaning, water supply, heating etc. or the user have to calculate them separately and enter them into the tool for further elaboration.

4. Result Variation in LCA in the Building Sector

The sector specific considerations presented in Paragraph 3 have a large influence on the following elements of an LCA and thus have a potential to have a significant influence on the results of an LCA:

- Goal and scope definition – description of the studied system and functional unit
- Inventory analysis - boundary setting, life cycle scenarios and the choice of allocation method, especially in the case of recycling, and inventory of the usage phase of buildings

Scenario modelling for predictions of service life and future energy use and maintenance is not very common in LCA methodology today but its potential has quite recently been noticed and has resulted in a working group within SETAC established to develop guidelines on scenario development, i.e. scenario frameworks, modelling scenarios and case studies (Ekvall, 1998). The SETAC-EUROPE report on LCA in Building and Construction has also recognised the importance of making more accurate scenarios of the future regarding, for example, replacement of materials and components, the service life of materials, components and buildings, and the kind and frequency of maintenance (SETAC, 2001).

The results from different LCA studies assessing the same material or product do often vary considerably even though they appear at first glance to be quite similar. These variations in results are significant and the difference between the results from two different studies can give diametrically opposite results in for example a materials choice situation. After studies of several LCA case studies it is suggested in **Paper II** that the reasons for varying results can be found in:

- Definition of goal, scope and focus
- Assessment method / methodological approach
- System boundaries
- Allocation procedure
- Valuation method
- LCA data

In the following will the influence of scenarios of the future, energy simulation, service life prediction, boundary setting, allocation and valuation be elaborated based on the findings in **Paper VI**, **Paper II** and **Paper III**.

4.1 The Influence of Scenarios of the Future, Prediction of Service Life and Energy Calculation Method on Results of LCA of Buildings

One of the main characteristics of buildings and constructions is the relatively long duration of their service life. The usage phase of buildings and constructions is, due to its long duration, a major contributor to the total environmental impact associated with buildings and constructions. The impacts are mainly related to the use of energy, both the extraction and conversion into usable form and the actual use of the energy. Recent lifecycle studies show that 70-90% of the total energy demands during a multi family building life cycle can be related to heating of the building, ventilation, domestic hot water and household electricity during the usage phase (Adalberth, 2000). The second largest part of the life cycle is, in terms of energy demand, the manufacturing of building materials for original erection of buildings as well as for maintenance. This part constitutes 10-20% of the total energy demand (Adalberth, 2000).

The energy demand in it self can be an important factor when a sustainable society is to be established due to the fact that a lower overall energy demand probably will have a positive influence on the energy related impacts on the environment, but not as an isolated entity. There are several different available sources of energy that can be used to satisfy the energy demand related to heating and domestic electricity in the building sector. Electricity can be generated based on hydropower and nuclear power, which is common in Sweden, or on coal, which is common in large parts of Europe, in combination with nuclear power. Nuclear power and coal as energy sources have in recent years been subjects for criticism due to the large impacts that an accident could result in, in the case of nuclear power, and due to the large emissions of CO_2 that are associated with coal based power generation plants. The society does today strive for a conversion of the power generation towards a use of renewable energy sources, e.g. solar power, wind power and especially bio fuels, in an attempt to lower the green house gas emissions. Whether it is correct or not to try to convert the energy generation to lower the emissions is not the issue in this thesis but political goals regarding these emissions have implications on the scenarios that should be deployed when assessing a building or a construction. This has implications on the results of LCAs and especially when the major part of the loads in the resulting environmental profile of an assessment is energy related.

Paper VI presents a study of the effects of different time perspectives and energy supply systems on the emission profile for a single family dwelling per year during its service life. The study was conducted by calculating the emissions generated during the process of satisfying a specific energy demand for a building with different energy systems and building service lives, i.e. several different usage phase scenarios were assessed. The technology development scenario regarding energy generation systems is taken from a study by the Swedish Environmental Protection Agency (Naturvårdsverket, 1998). The deployed scenario is a post materialistic scenario. The scenario is based on a willingness of the society to self regulate the energy use and by this self regulation the society could refrain from use of nuclear power and satisfy the energy demand by development and use of renewable energy sources. The scenario is based on the assumption that the CO_2-emissions are supposed to be reduced by 75% to the year 2050, i.e. the total emitted CO_2 is restricted to 4 Mton C per year and that the activity level in the society will increase with about 15 – 100%. Figure 4.1 presents the CO_2-emissions generated by four different energy supply systems. The CO_2-emissions also is presented in **Paper VI** together with other common energy-related emissions to air. The energy demand used in the calculations was calculated with ENORM 1000, which is a steady state energy calculation program.

There are several issues that influence the results presented in Figure 4.1 and consequently could have an influence on the conclusions drawn based on these results e.g. deployed scenarios, estimated service life, how to handle bio fuel related CO_2-emissions (exclusion or not), i.e. what considerations that have been taken into account in the emission calculations. Furthermore, the energy demand calculation program could also have a significant influence on the results. The influence is due to large differences in the results that depend on if the simulations are steady state or dynamic simulations. The values on temperature and temperature fluctuations that the simulations are based on could also have a significant influence on the result of energy demand calculations.

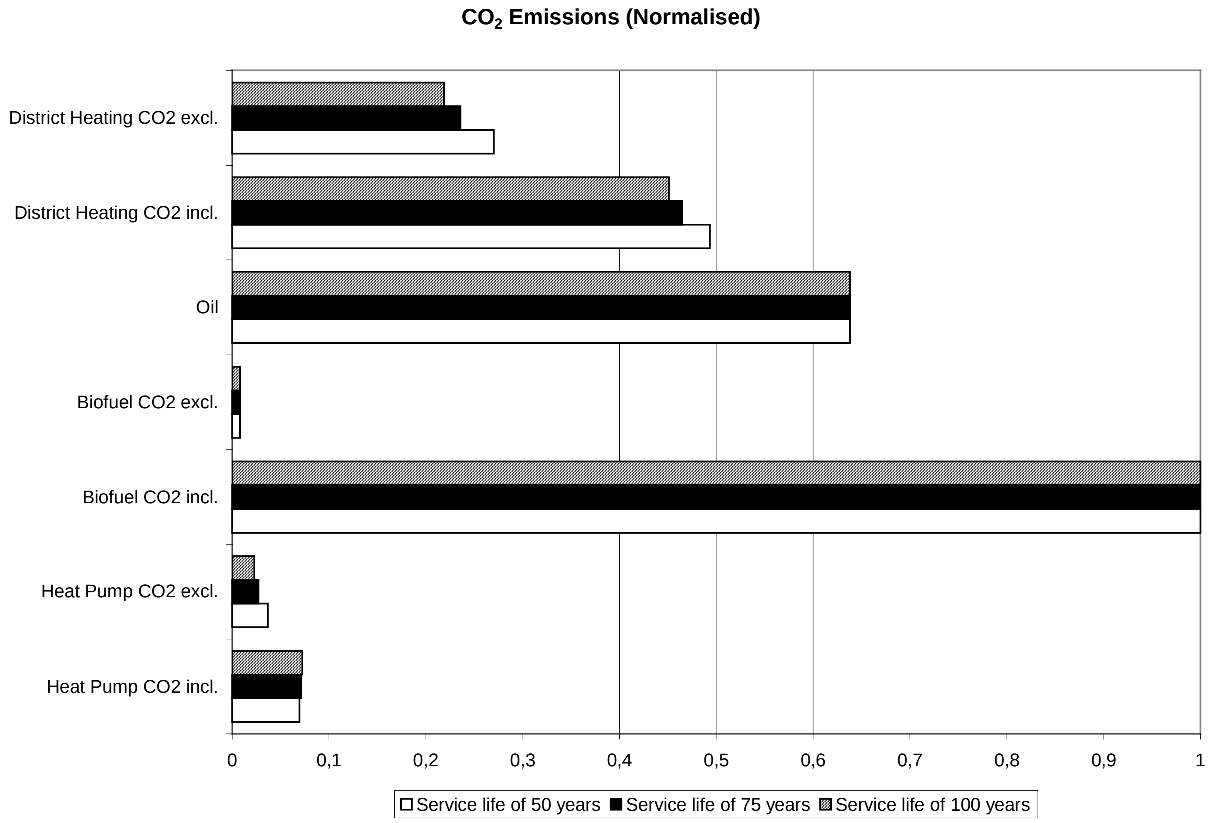

Figure 4.1 Normalised CO2 emissions for different heating systems based on the results presented in ***Paper VI****.*

The influence of which scenario, regarding technology development and the development of the society that is deployed, is not included in Figure 4.1 or in the study presented in **Paper VI**. There are, however, two other scenarios regarding technology development and the development of the society presented in the study by the Swedish Environmental Protection Agency (Naturvårdsverket, 1998), which has been applied to the same set of data as the set used in calculating the results presented in **Paper VI**. The added scenarios are two materialistic scenarios, which are based on the assumption that all activities increase with 50 – 200% and consequently that the energy demand of the society will continue to increase in the same pace as today and a scenario that assumes that the present situation will characterise the energy systems during the studied systems service life. The difference between the two materialistic scenarios is that one of them represents a decrease in CO_2-emissions by 50%, i.e. the 8 Mton C scenario in Figure 4.2, and the other represents a decrease with 75%, i.e. the 4 Mton C scenario in Figure 4.2. The full results of the study of the three development scenarios influence on the data set used in **Paper VI** are not presented in this thesis, but an example for the Heat pump heating system is presented in Figure 4.2 and an example for the District heating system is presented in Figure 4.3. The Figures illustrate the influence of four technology and societal development scenarios compared to the influence of three service life scenarios and how the CO_2-emissions, generated in the combustion process of bio fuels, are handled. The normalised figures are based on emission profiles calculated on an emission per year basis.

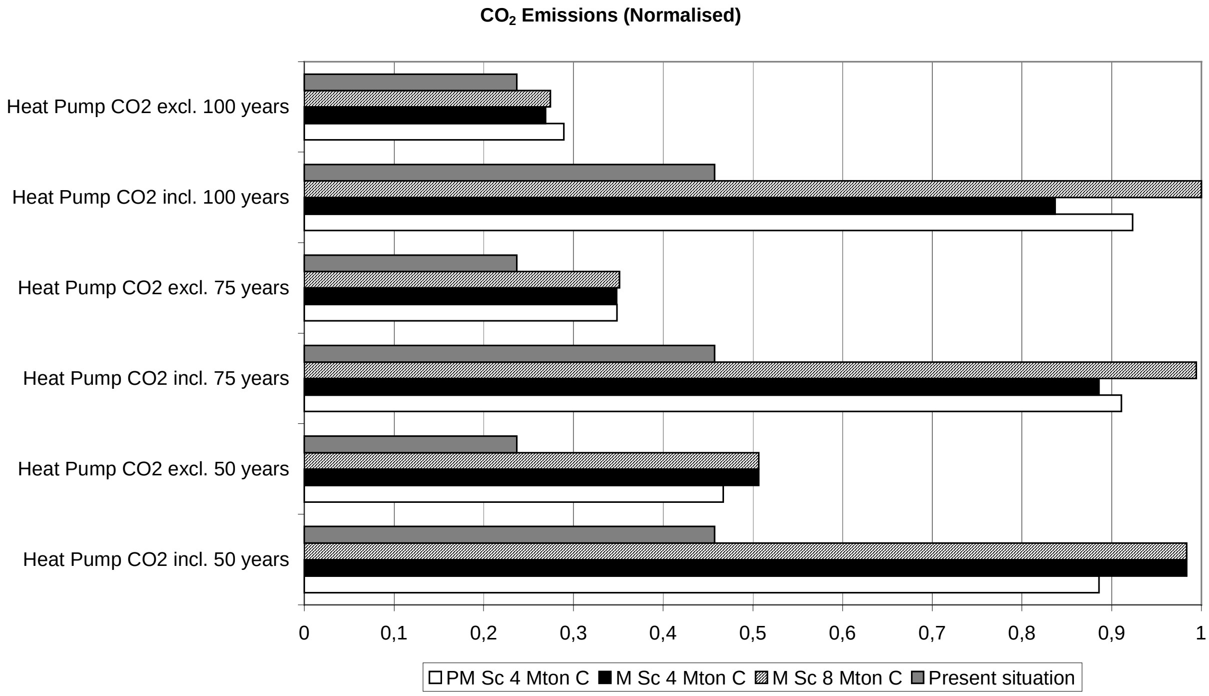

Figure 4.2 Normalised CO2 emissions for the Heat Pump heating systems presented for three different service life and four different technology and societal development scenarios. Based on the same background information as the results presented in ***Paper VI****.*

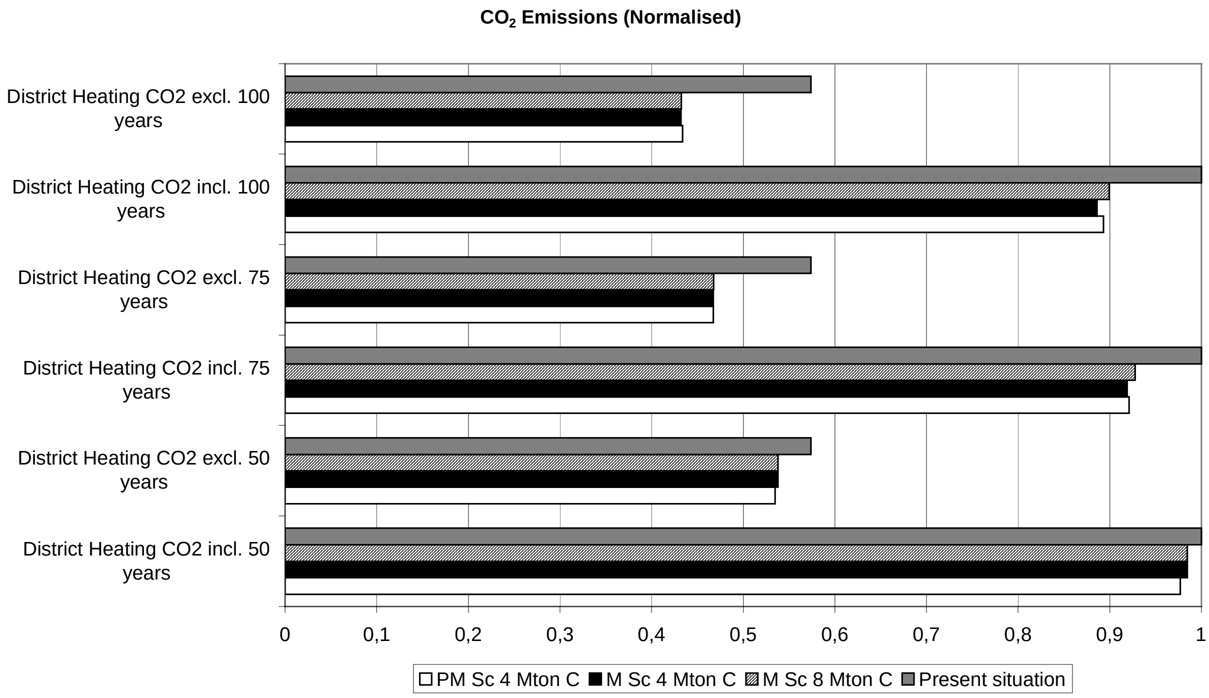

Figure 4.3 Normalised CO2 emissions for the District heating systems presented for three different service life and four different technology and societal development scenarios. Based on the same background information as the results presented in ***Paper VI****.*

4.1.1 Scenario Modelling (Scenarios of Future Development Regarding Technology and the Society)

The deployed scenarios regarding technology development and the development of the activity levels in the society have an influence on the results presented in Figure 4.2 and Figure 4.3. The influence is quite small compared to the influence of predicted service life and whether to include or exclude CO_2-emissions related to the combustion of bio fuels, except in the case of assuming the present situation as an acceptable approximation of future. It can be assumed that the influence is of the magnitude of approximately 1% to 50% in the studied scenarios. The influence of the scenarios is represented by the smallest and the largest difference between the normalised scenario that represents the highest level of emissions and the emission levels of the other scenarios. The influence of the chosen scenario is more significant if the heating system is electricity based rather than based on local combustion of bio fuels etc. as in the case of district heating.

The uncertainties, that are incorporated in an LCA due to use of scenarios like the ones used in **Paper VI** and in the calculations behind Figure 4.2 and Figure 4.3, are probably much larger than indicated. This because these macro level scenarios are, to some extent, based on political goals, which could shift as fast as the political agenda and the parliamentary situation. Estimates of the technical development rate are also afflicted with large uncertainties that also can be influenced by the parliamentary situation by subsidiaries and taxes, which make the deployed emission profiles very uncertain. This is, however, not a reason for not trying to include these kinds of scenarios in LCAs because they will most certainly increase the quality of the assessment compared to the procedure of applying today's average to represent future activities. A problem, however, is still to be able find data that is accurate to use for future processes.

4.1.2 Prediction of Service Life

It is indicated in Figure 4.1, Figure 4.2 and Figure 4.3 that the predicted service life of the assessed building also is an important area of concern to be able to perform relevant environmental assessments of buildings. The bars in Figure 4.4, that presents the Heat Pump HC-emissions, display the influence of the service life even better. The influence on the result of an assessment due to the predicted service life used in a study can be of the magnitude of approximately 10% to 40%, except in the case of applying a scenario that assumes the present situation to be an acceptable approximation of the future.

The service life of a building can be established based on a variety of considerations and parameters. The type of service life used in LCA-studies is of different origin and does not seem to be used based on their capability to approximate the service life of a building or a construction based on the actual context and type of building, but rather based on being the best available at the moment. There are several types of definitions of service life:

- Technical
- Economical
- Aesthetical

There are examples of at least the first two types of service lives represented in available life cycle studies, both LCAs and Energy assessments. The economic service life definition is e.g. used in an energy study of domestic buildings (Adalberth, 2000) where the service life of a domestic building is assumed to be 50 years based on the information that the average economic service life of an average Swedish domestic building is about 40-50 years. There are also several examples of the use of technical service life in LCAs, e.g. 50 and 100 years (Björklund et al., 1996) and 100 years (Persson, 1997). These service lives are presented in studies made in Sweden and are relevant in the studied context. There are, however, some similarities in the default service lives recommended for dwellings in several countries in Europe. In the Netherlands a recommended “standard” service life of 75 years is chosen and in the UK the default service life is 60 years (SETAC, 2001). These recommendations are valid for dwellings while the service lives for offices can be assumed to be significantly shorter, approximately 20 to 30 years (SETAC, 2001). The recommended service lives for offices based on generic figures used in the Netherlands and in the UK seem, however, not to be generally valid in Sweden. The average service life for offices are in Sweden likely to be quite similar to those used for dwellings but in the lower end, i.e. approximately 50 years.

A general problem in defining the service life of buildings is that it is not always clear which type of service life that sets the limit for the duration in time, i.e. if it is technical, economical or esthetical service life that defines the end of the studied life cycle. Which of the three that is critical to define the duration of the service life, is strongly dependent on the type of building, the type of activities planned to haunt the building and the geographical context.

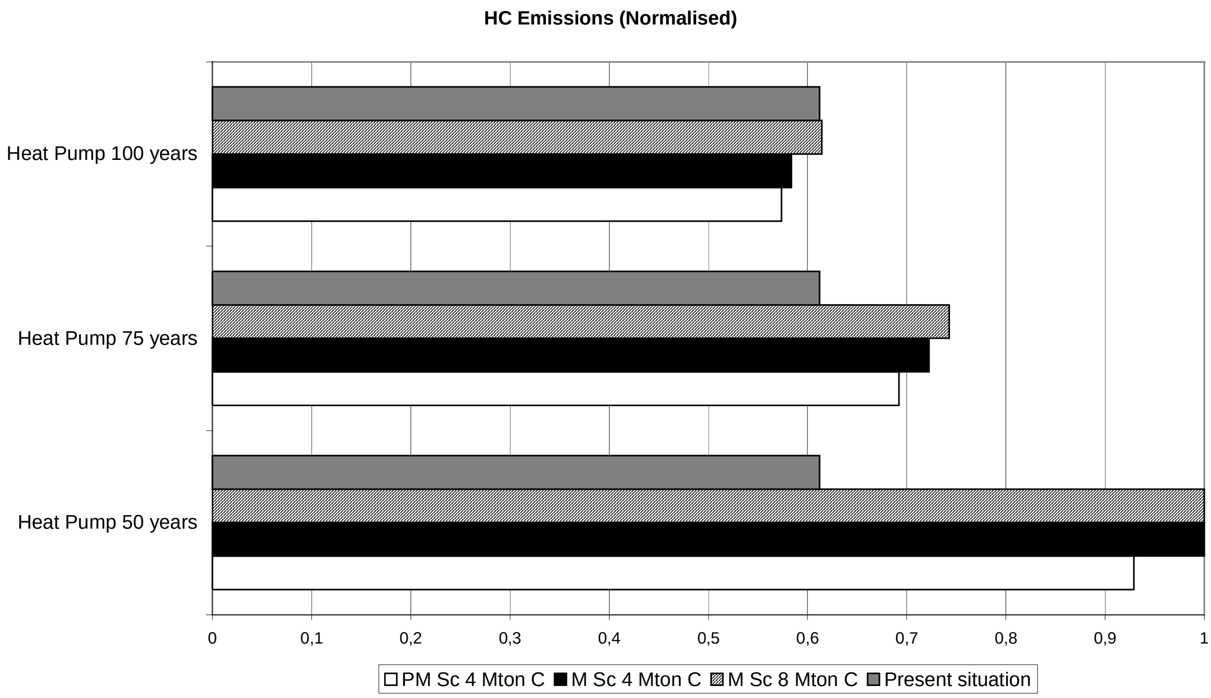

Figure 4.4 Normalised HC emissions for the Heat Pump heating systems presented for three different service life and four different technology and societal development scenarios. Based on the same background information as the results presented in ***Paper VI****.*

There is a need for a structured set of guidelines to be able to define the service life of buildings and constructions in a standardised way to enable comparisons between different buildings and constructions based on LCA results. An example of a first attempt focusing on the technical service life is the factor method presented in ISO 15686-1 (ISO, 2000c), which is a methodologically structured procedure to estimate the service life of buildings and when the method is fully developed and all factors are quantified then the factor method could be a practical tool to use in the pursuit of more accurate estimates of the service life of buildings when the technical service life is considered to be the critical. The focus of ISO 15686-1 is, at present, the prediction of technical service life and this focus is mainly due to the characteristics of the method, which involve quantification of performance requirements. This characteristic makes it not feasible to include economic or aesthetic consideration into the prediction of service life. The technical service life is, however, probably more accurate to use as the critical service life for privately owned buildings, which are not professionally managed.

4.1.3 Simulation of Energy Demand (Energy Calculations)

The influence of the method for establishing the energy demand of an assessed building or construction is not displayed in the previously presented figures. The influence of the choice of simulation program is instead presented in Table 4.1, which shows that the energy demand of the same building can vary considerably due to the choice of calculation procedure/simulation program.

Type of Framework	**Energy demand based on simulations [kWh/m^2 year]**	
	ENORM 1000	IDA
Massive wood	172	142
Conventional concrete	172	141
Light wood stud	167	169

Table 4.1 Energy demand figures including heating, domestic electricity and hot tap water, for a four stories dwelling in Stockholm based on simulations of three different framework systems (Borg & Eriksson, 1999).

The energy demand presented in Table 4.1 was calculated by applying the steady state ENORM 1000 program (Svensk Byggtjänst, 1996) and the dynamic energy demand calculation program IDA (Sahlin, 1996) on a four stories dwelling situated in Stockholm to be able to establish an approximation of the influence on the results of e.g. an LCA. The calculation procedure deployed in ENORM 1000 does not enable the user of the software to take the heat capacity of materials in the building envelope, which could participate in a temporal storage of heat, fully into account. There is a possibility to include the density and heat capacity of surface materials in energy demand calculations performed with ENORM 1000, but the design of the calculation procedure results in a marginal reduction of the energy demand. The difference in energy demand, which is approximately 15% - 20%, see Table 4.1, is probably due to the fact that the calculation procedure used in ENORM 1000 does not allow temperature fluctuations, heat-accumulation in frameworks, fittings and fixtures and solar radiation on the façade to be taken into account (Svensk Byggtjänst, 1996). It is noticeable that the difference in energy demand for buildings with light frameworks, such as wood stud framework systems, seems not to be affected by the differences in calculation procedures between steady state and dynamic simulation programs. The reason is probably that the steady state U-value method that is used is developed without considering the heat capacity and this makes the method reasonably accurate for light construction.

4.2 The Influence of Boundary Setting, Allocation and Valuation on LCA Results

Paper II and **Paper III** elaborate the influence of boundary setting, allocation and valuation on LCA results. Both these case studies are conducted on the material level, which means that no building specific processes, e.g. heating, cleaning and repair, and with those associated environmental loads, are included, but the studies are even though relevant for indications of the origin of result variations and their relative magnitude on both the material and component level as well as on the building level.

4.2.1 Boundary Setting

The influence of boundary setting in LCA has been studied by applying two assumed perspectives on a study of Swedish cold rolled hot-dip galvanised sheet steel production (Borg, 1998). In the first case the analysed process is viewed in a "gate to gate" perspective, i.e. a steel manufacturer conducting an analysis with his own process as the primary focal zone while the secondary focal zone (Trinius & Le Teno, 1999), upstream and downstream processes are omitted. The second case, on the other hand, is focusing on an analysis of the steel production process from a societal perspective, i.e. the primary focal zone constitutes of all processes from "cradle to cradle" including all upstream and downstream processes. The result from this case study was, as expected, that the applied boundaries in case one resulted in lower environmental loads than in the second case, see Figure 4.5.

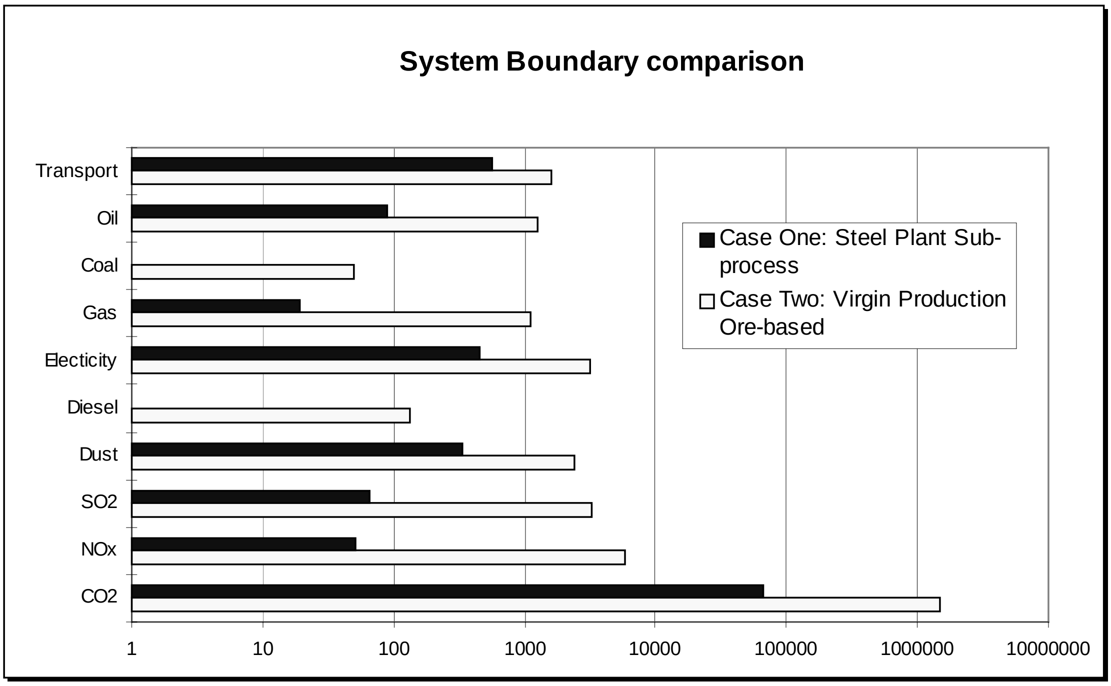

*Figure 4.5 Comparison of the environmental impacts regarding the system boundaries described in **case one** respectively in **case two**. Observe the logarithmic scale. Values are in MJ/ton for energy and in g/ton for emissions to air (**Paper II**).*

4.2.2 Allocation and Valuation

Although the activity of applying an allocation method to the collected process data is included in the inventory analysis step of an LCA, which is considered as being quite objective, the specific method chosen has usually a large impact on the achieved result. This is due to the disparate considerations and value choices that form the basis for different allocation methods. The statement presented above is generally applicable to both multi-functional process allocation and allocation in the case of recycling but the background articles are concentrated on allocation in the case of recycling, open-loop recycling.

The influence of different allocation methods on the results of an LCA has been displayed by applying four different allocation methods to LCI data regarding steel production (Borg, 1998) (Björklund et al., 1996) for three life cycles. The first cycle is a virgin steel production cycle, which include raw material extraction, production of steel and waste treatment. The second cycle include production of recycled steel and waste treatment. The third and final cycle do also concern production of recycled steel and waste treatment, but in this case it is final waste treatment due to the fact that it is the final cycle in a three-cycle scenario. The four allocation methods are the SBI-method (denoted as Andersson & Borg in Figure 4.6 and 4.7) (**Paper I**), the Cut-off method, The Disposal load method (Östermark & Rydberg, 1994) and finally the 50/50 method (Ekvall, 1994), which all are briefly described in Paragraph 5. The results from the first study presented in Orlando March 1998 (**Paper II**), see Figure 4.6, are presented as allocated data for three life cycles.

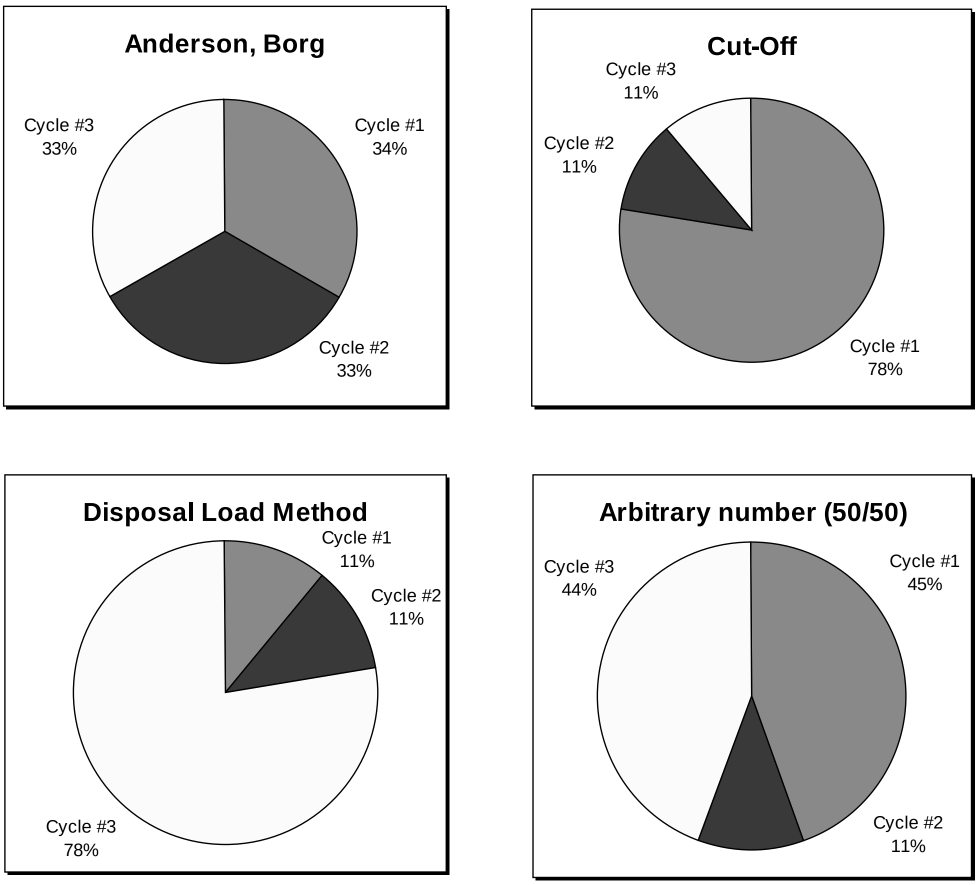

*Figure 4.6 The allocation of CO_2 emissions on the life cycles #1-3 according to four different allocation methods (**Paper II**).*

While the results from the latter study (**Paper III**) are presented as allocated data for three life cycles on which five different valuation methods are applied, see Figure 4.7. The same LCI-data and the same scenarios are used in **Paper II** and **Paper III** The purpose is to display the relative influence of different valuation methods on the result compared with the influence of the four allocation methods. The Anderson & Borg allocation in Figure 4.7 is the same allocation method as the SBI method (**Paper I**), which is briefly presented in Paragraph 5.

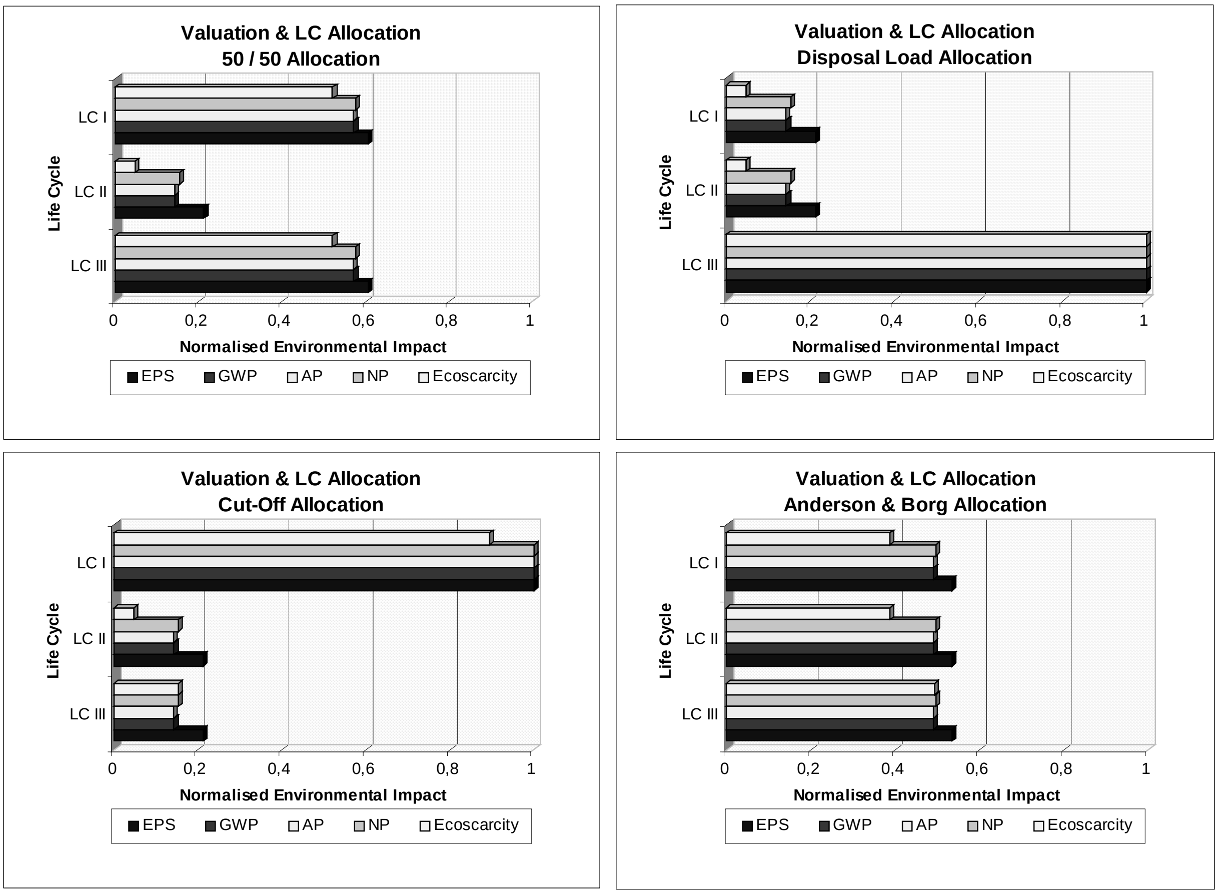

*Figure 4.7 Normalised valuation results after allocation of LCI data (**Paper III**).*

5. Allocation of Environmental Loads

Allocation of environmental loads within the context of LCA has as a primary purpose to partition the loads generated within a system between the processes and products included in the system. The ISO definition of allocation is:
”Partitioning the input or output flows of a unit process to the product system under focus”. (ISO, 1997)

Allocation may be carried out mainly in two types of situations:
1. The process under study is a multi-functional process, a process that includes one or more unit processes that deliver more than one function
2. The process under study is a part of a recycling system, e.g. the function delivered by one process can or will be recycled and used in another process

Partitioning the input or output flows of a unit process is conducted by applying an allocation procedure, where the input or output flows of the unit process are to be distributed between the products generated by that process. The former description is a general description, which is accurate in the case of multi functional processes. In multi functional processes the products (co-products) are usually produced simultaneously or successively but within a short period of time, e.g. electricity and heat generation in a combined energy plant (Frischknecht, 2000).

In case of allocation over recycling or reuse cascades, where the material undergoes a change in the inherent properties (open-loop recycling), is the task rather to distribute the environmental loads between succeeding life cycles than to a number of simultaneously produced products. Open-loop recycling can, however, be regarded as a special case of multi functional processes according to ISO 14041 (ISO, 1998) that also states that a stepwise allocation procedure shall be applied. The outline of the procedure in ISO states that the first option is either to divide the unit process or to expand the studied system and by that be able to avoid allocation. The second option is to distribute the inputs and outputs based on physical relationships between products and the third alternative is a possibility to use other relationships as a basis for allocation, e.g. economic value. ISO 14041 has stated that the same principles and procedures are applicable in the case of recycling as for multifunctional processes. To be able to handle allocation in the case of recycling as a special case of multi functional processes allocation necessitate several additions that clarify the ISO view on open-loop allocation procedures. Examples of these clarifications are that "*changes in the inherent properties of materials shall be taken into account*" and that allocation procedures should use physical properties, economic value or the number of subsequent uses of the recycled material as the basis for allocation (ISO, 1998).

The description of the two different types of systems, in which allocation is performed, indicates that these systems are separated and can be studied as separated systems. This is, however, usually not the case. It is instead rather common that the systems subjected to an LCA study consist of unit processes that are multifunctional processes, recycling processes or both multifunctional and recycling processes at the same time (Frischknecht, 1998).

The focus of the remainder of this paragraph is on allocation in the case of recycling and on products that experience changes to the inherent properties, i.e. open-loop recycling.

5.1 Allocation in the Case of Recycling

Allocation in the case of recycling is the distribution of the environmental loads from raw material based production, secondary material based production, recycling procedures, waste treatment and attributable transportation in-between the products participating in recycling loops, see Figure 5.1.

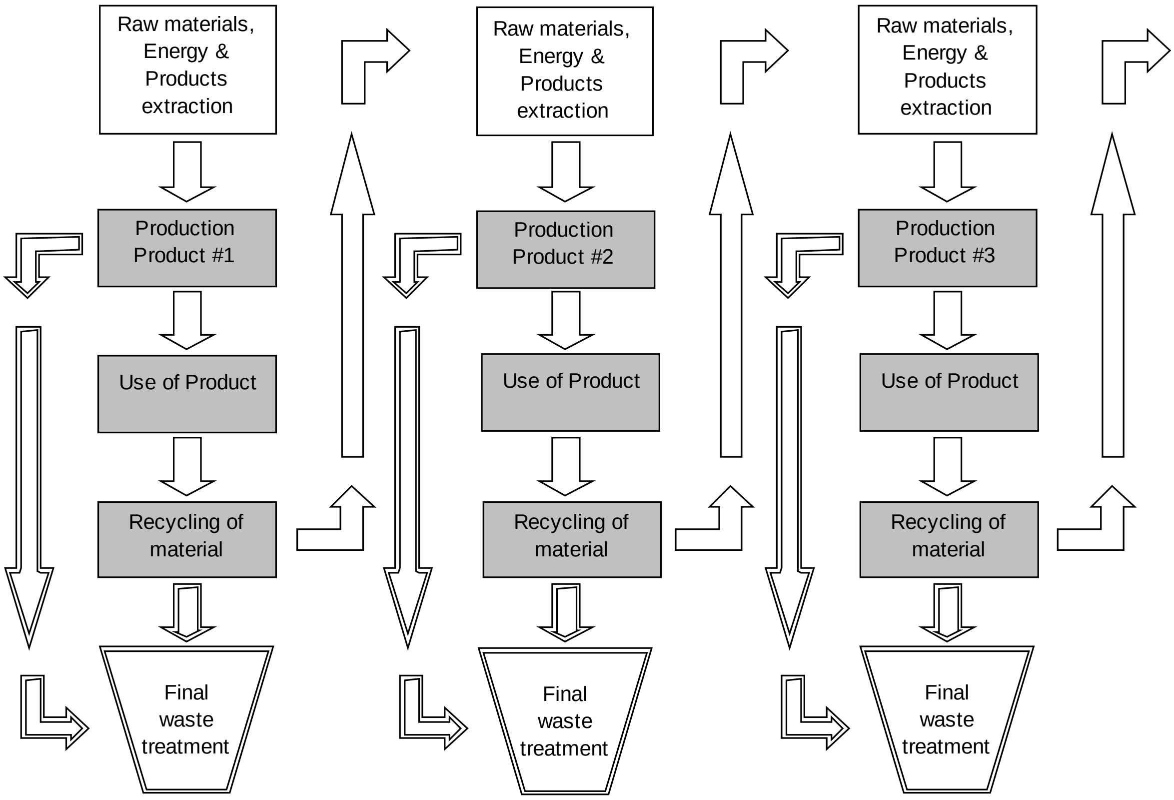

Figure 5.1 Cascade recycling system.

The reason for applying allocation methods to the relatively objective data collected in the inventory phase of an LCA, and thereby jeopardising the objective character of the inventory, are e.g.:

- That a material or product that can be recycled or reused and be a part of another material or product life cycle, should not be attributed the whole material related environmental load
- That products that are designed to enable recycling and reuse should be promoted
- That the use of recycled and reused materials should be promoted

The reason why the application of an allocation method to the collected data jeopardises the objectivity is that most allocation methods in some way are based on subjective judgements regarding the choice of allocation principles. This subjective character of most allocation methods is further stressed by the fact that one of the major criteria for a good allocation method is that it should be regarded as "fair", i.e. acceptable to the users of the LCA results.

5.2 Principles for Allocation in the Case of Recycling

Allocation in the case of recycling is usually divided into two types: Closed-loop and Open-loop allocation. Closed-loop allocation treats problems that occur when the studied system is characterised as a Closed-loop recycling system, which means that a product or material is recycled to the same function each time, for example a beam is recycled into a beam which is recycled into a beam and so on in infinity. These types of systems are usually easy to handle with system expansion because each life cycle is the same and, therefore, no allocation is needed.

Open–loop allocation on the other hand addresses more complex systems. These systems do not produce the same product in each cycle and do, therefore, need more complex methods for allocation than closed-loop recycling systems. There are several principles and a vast number of methods available for open-loop recycling. The first principle to be considered in all allocation situations is to try to avoid allocation by expanding the system boundaries or to divide the studied system into two or more subprocesses. Commonly used principles for Open-loop allocation when allocation cannot be avoided are (Finnveden, 1994):

- Natural causality, e.g. physical, chemical, biological or technical causality
- Social causality, e.g. economical value of products, socio-economic relations
- Physical quantities, e.g. mass, volume, area, energy, exergy or number of molecules
- Arbitrary number, e.g. 50/50 between two products

There are several allocation methods available based on these principles and the most commonly used are based on social causality or arbitrary number. ISO 14041 (ISO, 1998) on the other hand has suggested another set of bases for allocation, which are:

- Physical properties
- Economic value
- The number of subsequent uses of the recycled material

5.3 Open–loop Allocation Methods

There are several accepted allocation methods in use today and each of them represents different opinions about which base for allocation to use, what constitutes a “fair” distribution of the assessed material’s, product’s or system’s environmental loads etc. The use of the term ”fair distribution” indicates that the choice of allocation procedure is strongly related to personal value judgements and is therefore subjective and that the methods may be based on subjective values as well. Ekvall and Tillman (1997) and Klöpffer (1996) have presented a number of different criteria for a “good allocation procedure”. The presented criteria are that a good allocation procedure should be:

- Based on effect-oriented causalities
- Acceptable to the users of the LCA results
- Easy to apply

Furthermore, the allocation procedure should be designed:

- With internal logic
- Without double accounting
- To be feasible at a low level of information
- To give incentives for production and use of secondary raw material

These criteria are on the whole in accordance with the principles presented in ISO 14041. The ISO standard does, however, not mention the easy to apply/feasible at a low level of information aspect, but does instead put stress on the aspects of internal logic/double accounting and effect-oriented causalities by emphasising the importance of good approximations of the input-output relationships and characteristics. Furthermore, the standard emphasises that the sum of the allocated inputs and outputs shall equal the sum of the unallocated inputs and outputs of a unit process.

There are a large variety of allocation methods that are available today and that have been and still are used in LCA studies of different types of systems. These methods represent several of the above-mentioned bases for allocation. A commonly mentioned and cited allocation method, when the assessed material is used in more than one product (Open-loop recycling of materials), is *the 50/50 method* (Ekvall, 1994). This method is based on arbitrary number and recommended in the Nordic Guidelines for LCA (Lindfors et al., 1995). *The 50/50 method* promotes the use of recycled material instead of virgin material, as several other methods do in one way or another. Examples of other methods are *the extraction-load method* (Östermark & Rydberg, 1994) and *the disposal-load method* (Östermark & Rydberg, 1994). Both of these methods are based on social causality.

Other methods are based upon the opinion that each product should only be assigned the environmental loads caused by production of the product, and thus allowing the following cycles to be disregarded, as in *the cut-off method*. These kinds of methods are usually used when information about the first cycle is known, but only scarce information is available concerning the following cycles or if the loads that potentially can be allocated, are insignificantly small. *The cut-off method* can also be used with more sophistication by applying a set of cut-off criteria that would give the method more rigid and comparable results. These cut-off criteria could be based on economic considerations (ECSC, 1999). An example of economic cut-off criteria could be to develop a set of rules to determine the zero value point in a material's, product's or systems life cycle (Howard, 1998).

A third kind of methods takes the quality reduction between life-cycles into account and they are based on the assumption that the quality of the material after use is too low for direct re-use, i.e. meaning that recycling processes are a necessity for further use of the material. Examples of this kind of method are those used in the EPS system, *the EPS method*, (Ryding et al., 1995) and in the Danish EDIP project, *The EDIP method* (Wenzel, 1998).

There are also a number of methods developed with multi-recyclable materials and products in mind. These methods are primarily based on the third basis for allocation presented in ISO 14041 (ISO, 1998) "the number of subsequent uses of the recycled material". An example of this type of method is the SCI-method developed by A. Amato, L. Brimacombe and N. Howard for *the Steel Construction Institute (SCI)* in the U.K., (Amato et al., 1997).

Yet another basis for allocation is economical value of materials and components in different stages of the life cycle. An example of methods based on economical value is the market-based approach to allocation (Ekvall, 1999), which is an approach that aims at taking the market reaction, in economical terms, to changes in the demand for recycled materials into account. Further examples are presented in Paragraph 5.4 and 5.5.

5.4 Allocation Methods Used in the Case of Recycling and Presented in LCA Methodology Reports and Used in LCA Tools for the Building Sector

The allocation methods presented so far are methods that are frequently mentioned in literature and articles concerning the field of allocation, but these methods are not the only methods available today. There are today several allocation methods presented in LCA methodology reports, both tool-associated and detached, for use in the building sector. Below is a selection of allocation methods applicable in the case of recycling briefly presented, which are used in LCA tools or methodologies developed for use in the context of the building sector. The reasons for choosing the tools in which the allocation procedures are incorporated are presented in **Paper VII**. These building related methods are based on different basis for allocation, but a majority has in common that the aim is to take the actual characteristics of the studied material or component into account, in one way or another.

The procedures presented are taken from the methodology reports or related literature on which the tools studied in **Paper VII** is based. The tools studied in **Paper VII** are; "ATHENA^{TM}" (ATHENA Sustainable Materials Institute), "Envest" (BRE), "Eco-Quantum 3" (IVAM), "BEAT 2000" (SBI), "BEES" (US EPA). These tools are developed at different points in time and this is reflected in the allocation procedures that are incorporated or recommended.

The topic of allocation in the case of recycling is in the ATHENA^{TM} tool handled by adopting an existing allocation procedure, which basically is in accordance with the Canadian Standards Association (CSA) guidelines for life cycle assessment (CSA, 1994). The approach towards allocation is developed in the early 1990-ies, which is reflected in the procedure. This is apparent due to the fact that economic parameters as a basis for allocation are not mentioned as an alternative to the three basis for allocation that are proposed in the standard. The CSA guidelines for life cycle assessment state that the allocation procedure, which is recommended in the ATHENATM tool, is based on a set of principles that should be applied in certain situations, if feasible. The first approach states that the allocation should be based on the actual mass flows between product #1 and product #2, which requires that both production system #1 and #2 are known. If this approach is not feasible, two arbitrary methods are proposed and presented in order of complexity. The first option is to make an allocation based on the principle that the avoided disposal can be allocated to the product being recycled and the second is based on an even distribution (50/50 allocation).

The approach to allocation is somewhat different in the Envest tool. The open-loop allocation procedure presented in the report "BRE methodology for environmental profiles of construction materials, components and buildings", and that is used in the envest design tool (BRE, 2000), is based on economical value of residuals (Howard et al, 1999). The aim of the approach is to distribute a proportion of the impacts originating in the production phase to the wastes that arises. This distribution is based on the economical value of the residuals in proportion to the value of the original products. The recyclability and reusability properties of the studied materials or components, which is used in the approach, will be based on current recycling achievement. This position is based on the view that to use the potential recyclability and reusability properties then we have to rely on future decision makers to respond to the predictions made today and that future markets will have a demand for the materials or components that fulfil our assumptions about future markets.

Another allocation method used in the building sector is the Eco-Quantum method (ECSC, 1999). The description of the general method is taken from an ECSC report “LCA for Steel construction, Methodology and preparation for data collection” due to the fact that it has been difficult to trace the original source from which the method presentation in the above article is taken. Information regarding the methodology of Eco-Quantum is, to my knowledge, very scarce and information is mainly presented at different international conferences as promotion material (Mak et al, 1997) (Kortman et al, 1998). The method is based on the first step in the procedure for allocation according to ISO, i.e. expanding the system boundaries to avoid allocation, in combination with the opinion that when the inherent properties of the assessed material do not change when recycled, then the use of that material displaces the use of virgin material and the situation can then be considered as a closed loop. The allocated load is calculated by multiplying the share of virgin and recycled material in the studied product with the environmental profiles associated with the production of the two materials. It is not clear, however, if this procedure is a general procedure or just a specific procedure for applicable steel products. It is, however, indicated in the results of the questionnaire, presented in appendix A in **Paper VII,** that the method could be generally applicable due to the fact that the procedure include economic cut-off rules that make a distinction between products with positive and negative economic values.

The Danish BEAT 2000 tool has not an incorporated default allocation procedure in the case of recycling and thus gives the user of the tool the opportunity to choose the type of allocation that the user finds suitable. The allocation procedure that is recommended in the BEAT methodology report “Miljødatablade for bygningsdele” (Holleris Petersen et al, 2000) is to use a traditional cut-off allocation in the case of recycling. This is motivated by the large uncertainty that the long service life of buildings and building products induces on an assessment and that most building products are subjects of “low-level recycling”, which indicates that loads, that can be allocated, are insignificantly small.

5.5 Other Methods for Distribution of Environmental Loads in the Case of Open-loop Recycling With a Special Focus on the Building Sector

During the work with LCA and execution of LCA studies, it was often found that it was hard to find a suitable life cycle allocation method that could give multi-recyclable materials and products a “fair” treatment. The general drawback of most methods available at that point in time was that they did not consider the specific characteristics of the studied materials or products. As a consequence of this drawback Johan Anderson, at the SBI in Stockholm, and I began to think about how to establish a life cycle allocation method that did take the characteristics of materials into account. This work resulted in a method that was originally presented in a SBI report titled “A Quantitative Methodology for Assessing Environmental Impact of Recyclable and Reusable Products” (Anderson & Borg, 1998) and later at the International Conference on Steel in Green Building Construction in Orlando, March 1998 (**Paper I**). The method is nowadays known as the SBI-method and it is based on the idea that cascade materials that are included in products or products themselves should be treated in a ”fair” way when allocation is concerned. In this context, fair treatment means that the environmental advantages of the recyclability and reusability i.e. lower the demand for energy and resources and lower emissions to air, water and ground, are taken into account.

In the method, the recyclability and reusability and the advantages associated with those characteristics, are taken into account by introducing the concept of yield and by the concept of system extension (Ekvall, 1998). The yield is defined as the percentage of a product that ”survives” one life-cycle stage and enters the next. The ”re-entry enabling process” is either reuse or recycling, i.e. reused products or recycled material. A representation of the yield is presented in Figure 5.2. Furthermore, to clearly separate the product related environmental loads that are affected by an allocation from those that are not, the formulas in the SBI-method are divided into a resource and a product related part. The resource related loads are distributed between the cycles based on the recyclability or the potential recyclability of the material, while the loads, that are specific for the product production process, fully burden the assessed product.

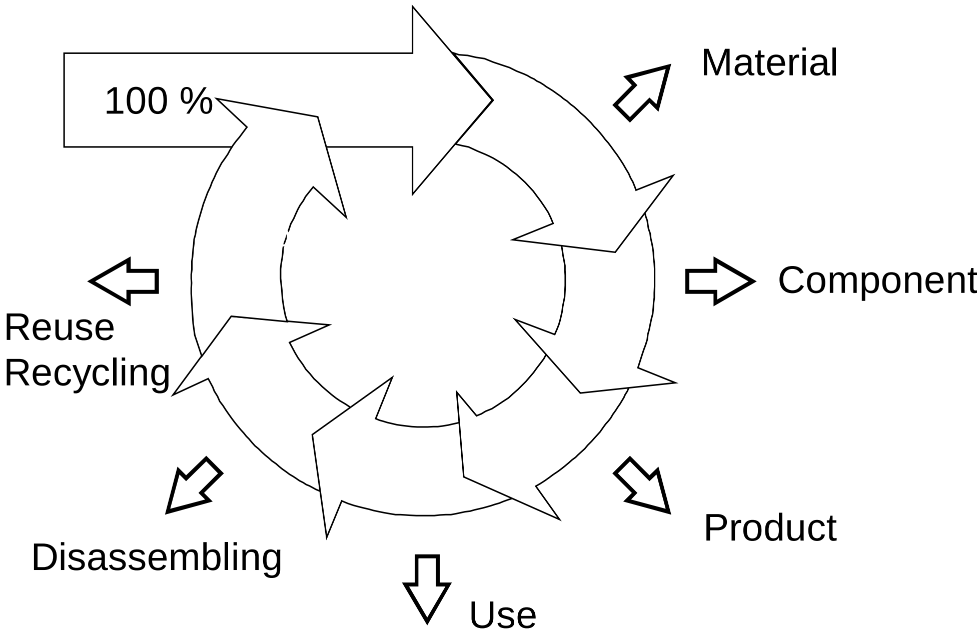

*Figure 5.2 A schematic representation of the Yield, the circle, and losses due to different processes, the small arrows, during the life cycle for a product (**Paper I**).*

The above mentioned method did not, however, become a generally applicable method, i.e. applicable regardless of the characteristics of the material or product, but rather a very good method to use in the case of multi-recyclable materials as steel, aluminium and glass. This result initiated further work to develop a generally applicable method that enable a better inclusion of material and product characteristics and aim at being used in the building sector with its specific implications (**Paper IV**). This work was executed in co-operation with Jacob Paulsen and Wolfram Trinius at the KTH, div. of building materials, in Stockholm.

The development of the method was based on three principles (**Paper IV**):

1. In order to allocate environmental loads from raw material production forward to a succeeding product life cycle, the proceeding lifecycle has to take responsibility for the upgrading of the recycled material to a clearly defined and relevant level.
2. Only loads from the part that can be expected to be recycled shall be allocated forwards. Material characteristics and design of products can be important factors to estimate the ratio between the waste fraction and the recycled fraction.
3. The quality reduction between the materials in two subsequent product life cycles is indicated by the ratio between the market value for the material in the products.

Furthermore, the goal of the development was to give the new method the characteristics to be able to handle situations where the recycling of materials and products rather is a form of waste treatment than recycling. The work resulted in a method that is based on the idea that economic value of materials and residues in combination with the recyclability or reusability of materials, products or components can be used as a basis for life cycle allocation methods. The use of Economic value as a basis for allocation, both when multi-functional processes and when allocation in the case of recycling is addressed, has earlier been proposed by for example Huppes (1994), Frischknecht (1998), Ekvall (1999) and is proposed as a basis for allocation in the ISO 14041 (ISO, 1998). The difference in the presented method compared to earlier proposed methods, that include economic value as a basis for allocation, is that the proposed method combines the economic value with an approximation of the recyclability and reusability by the use of a design factor, which represents the recyclable fraction. Similar thoughts, regarding how to handle allocation, are represented in the allocation procedure developed by the BRE (Howard et al, 1999) and an allocation procedure developed at the Swiss Federal Institute for Materials Testing and Research (EMPA) (Werner & Richter, 2000).

The problem with the long service life of products in the building sector is dealt with by introducing the concept of a virtual parallel time perspective, which enables practitioners to deal with the problem of establishing acceptable values on recyclability and reusability. This is achieved by using current data on primary production as well as for recycling processes, i.e. treating the allocation as if the two processes occur at the same point in time even though the secondary production could occur as far as 100 years into the future. The aim is to engage the parties representing both virgin and recycled material producers to establish an acceptable relation between environmental loads originating in primary and secondary materials and components production and acceptable ratios of recyclability and reusability. An extensive presentation of method can be found in (**Paper IV**) [***].

[***] There is a misprint in **Paper IV**, Page 228, Equation (10). The equation should be read:

$L_{Allocated \rightarrow RA} = L_{forward\ V \rightarrow RA} - L_{backward\ RA \rightarrow V} - L_{forward\ RA \rightarrow RB} + L_{backward\ RB \rightarrow RA}$.

6. The Usage Phase of Buildings

There are two major approaches to how to design LCA tools/methodologies for assessment of different products represented among the tools and methodologies studied and presented in **Paper VII**. The majority of the tools is based on a bottom up approach while the Envest tool is based on a top down approach. The difference between the two approaches when the usage phase is concerned, is that the necessary information on the building level that makes it possible to fully incorporate the usage phase related loads into an LCA, is not available in the bottom up approach. The top down approach on the other hand enables incorporation of adequate input from the building level into the assessment of a building or a construction. The usage phase can consequently be regarded in a more accurate way, i.e. based on the actual situation and context, and more accurately include and consider activities like energy demand, maintenance, service life etc. The tools based on a bottom up approach usually require generic values on the aforementioned activities to represent the usage phase and these are usually not adaptable to the actual context. This is usually not a major problem when assessing whole buildings or constructions as the generic values usually approximate reality with sufficient accuracy.

6.1 Current Practice Regarding the Usage Phase of Building Materials and Components

A problem, however, has been identified when LCA is used as decision support in the case of choosing building materials and components. An inventory of several LCA tools (IEA, 1999) and case studies (Person, 1997), (Björklund, 1996) has indicated that the usage phase is handled by taking into account the number of replacements for building products and by estimating the operational energy consumption, which is calculated on the building level and not connected to specific product data. The influence on the environment of the maintenance and the emissions from materials to the indoor and out door environment is excluded.

Especially Maintenance has been recognised as an important factor to consider in LCAs in the building sector, but a lack of knowledge of how to deal with it in a proper way has been recognised (SETAC, 2001). For the purpose of product comparison, the whole life cycle of the product has to be taken into account (ISO, 1997), (ISO, 2000c). Even though both the SETAC working group and ISO 14025 have underlined the importance of including the whole life cycle in a LCI/LCA for product comparison. A tendency towards exclusion of some aspects of the usage phase for building products is pertinent to the industry. Type III declarations that are addressed to consumers shall include the whole life cycle from cradle to grave, while declarations addressed to the industrial/commercial end-users do not have to be considered from cradle to grave. This opportunity to exclude certain stages of the life cycle is based on the assumption that industrial/commercial end-users have knowledge of the impacts in the usage phase and, therefore, can include them if necessary. An inventory of type III declarations in Sweden (Erlandsson, 1996), (Erlandsson & Andersson, 1997), Finland (Vares, 2000), (Häkkinen & Vesikari, 1997) and Norway (NBI, 1999) has been carried out, all showing that the declarations are primarily based on cradle to gate assessments and thus excluding the usage phase.

6.2 A Proposal of a Bottom Up Approach for Inclusion of the Usage Phase for Building Materials and Components

In **Paper V** an attempt has been made to identify the sources of environmental loads that can influence the environmental flows in the usage phase, either directly or indirectly connected to a specific building product choice. The identified sources constitutes a basis for determining if it is relevant to include the usage phase in an LCA of building materials and components. The following sources have been identified as having potential influence on the magnitude of the loads originating in the usage phase:

- Emission to the indoor environment from products
- Emission to the outdoor environment from products, e.g. leaching of hazardous substances
- Interference with the resource flows in building systems, e.g. energy use or water use
- Consumption of auxiliary products and resources for maintenance, e.g. cleaning or painting

The six boxes in Figure 6.1 represents schematically the sources of environmental loads from the whole life cycle that can be caused by a specific product choice. The four boxes above the dotted line refer to the four identified sources of loads (L2 to L5) that can contribute to the impacts in the usage phase caused by a product choice. The loads from the production process (L_1), also called the cradle to gate inventory together with the loads from waste treatment (L_6) can normally be estimated on the product level, regardless of the application in a building.

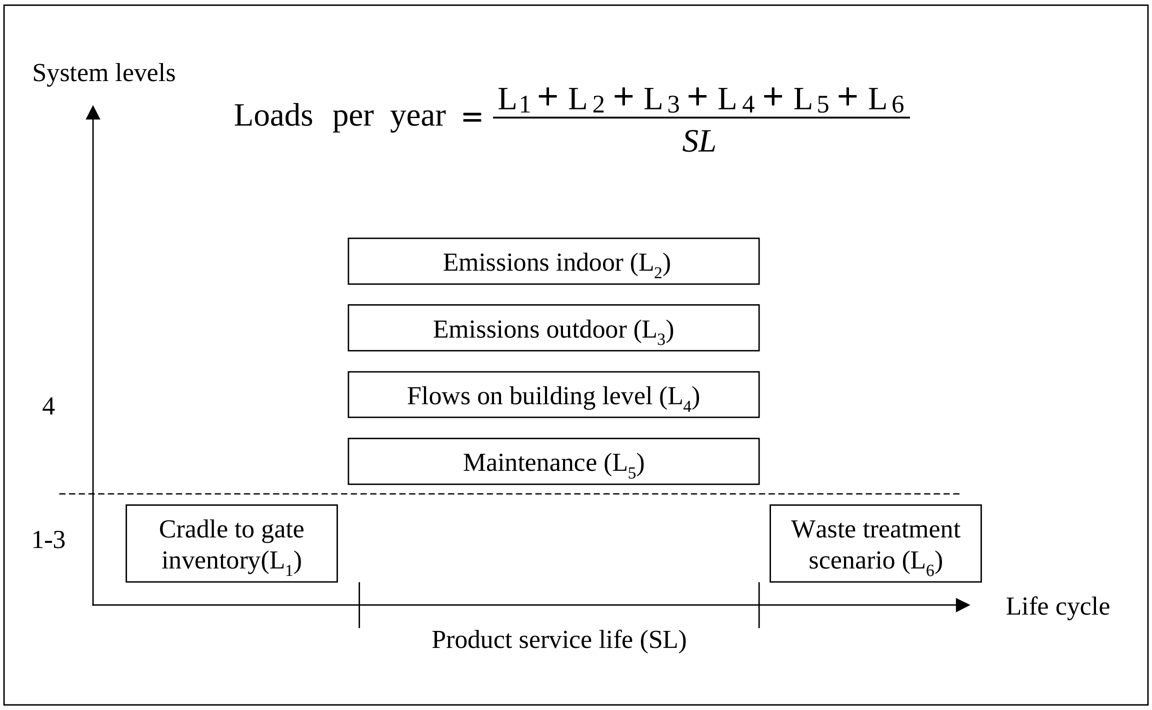

*Figure 6.1 Relevant environmental loads caused by a specific product choice, taking the whole life cycle into account (**Paper V**).*

The summation of the loads L_1 to L_6 will result in the total environmental loads caused by a specific product choice through the service life of the product. However, if a product comparison has to be done, it is important that the comparison is done on the same basis.

Since two products for the same application can have different service lives, this has to be taken into account. Therefore, the service life has to be estimated for each of the products that shall be compared.

The approach is based on a two-step procedure in which the first step concerns the identification of the potential influence of a certain product choice on the environmental loads generated during the usage phase. If the product choice has been identified to have a significant or significantly different environmental load in the usage phase, compared to other alternatives based on the current application, then the type of loads and an estimation of their magnitude have to be established, see Figure 6.2.

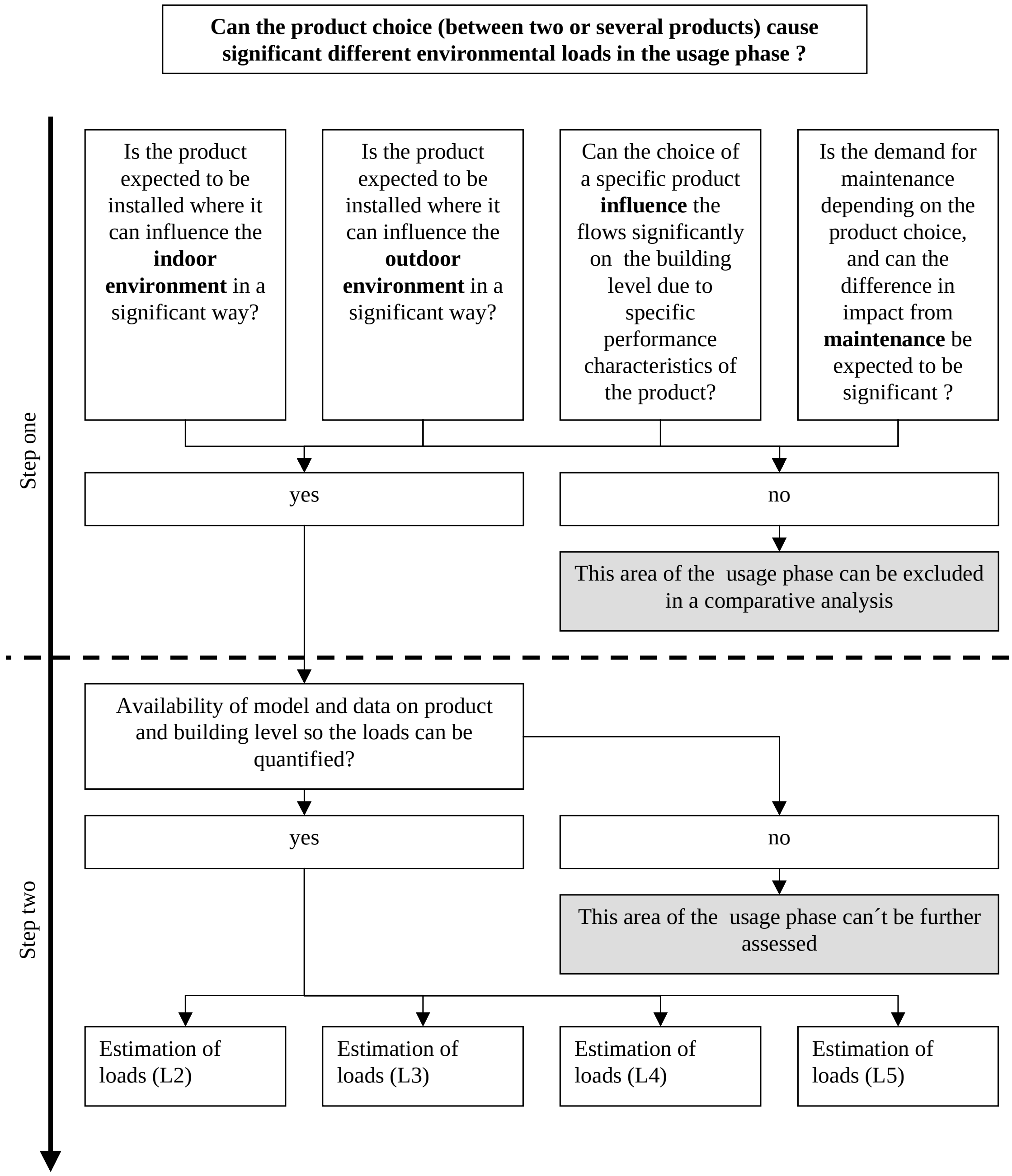

*Figure 6.2 Procedure to estimate environmental loads originating in the usage phase (**Paper V**).*

Methods for estimating the magnitude of the environmental loads originating in the four identified sources are still under development and will briefly be discussed in the following.

The relevance of including the indoor environment in a specific material choice situation depends to a large extent on where the analysed component is intended to be applied in the building and in what type of building. If the indoor emissions are expected to be important, the possibility to estimate the loads depends on several conditions. A model is needed to explain the transport mechanism that causes the emissions and to identify the substances in the product, which transforms into emissions. Furthermore, a model is also needed to be able to identify and to consider the building specific conditions that influence the emissions in relation to actual transport mechanisms.

Emissions to the external environment can be expected for some types of building products due to leach of different substances e.g. PCB and zinc. The relevance of including emissions to the outdoor environment in a product choice depends on the potential effects on the surroundings. Materials that contain documented hazardous substances or materials that contain even small amounts of hazardous substances, but are used in large quantities could be a basis for including emissions to the outdoor environment in an assessment.

In some cases the choice of building products can indirectly affect the environmental loads of the whole building by influencing the resource flows through the building. Water and energy are two types of resource flows that can be influenced by specific product choices. Several case studies have shown that energy use during the usage phase for a building is very large compared to the embodied energy in the building products (Björklund et al, 1996), (Adalberth, 2000). If a choice between two (or more) building products will result in significantly different energy use for the whole building, it is important to include the use related energy aspect in a product LCA. The differences in environmental burdens for production of the building product can thereby be set in relation to the marginal difference in impacts in the usage phase, examples are given in the articles "Building physics –No way around it" (Jóhannesson & Levin, 1998) and "The role of energy use predictions in the choice of building materials" (Paulsen & Augenbroe, 2001). The relevance of including the impact on energy use of a material choice, seems most relevant for those materials in the building that significantly influence the thermal storage or the heat loses trough the building envelope.

Many building products require some kind of maintenance, e.g. cleaning and painting, during their service life to maintain the desired function or service. The environmental loads from maintenance can be significant due to the long service life of building products (Paulsen, 1999), but there has to be a significant difference in the demands for maintenance between two or more product alternatives before it is relevant to include maintenance aspects. To be able to estimate the potential environmental loads from maintenance, a model is needed to estimate the resource use for maintenance as a function of a product choice and a building context. The amounts of resources used are depending on the types of maintenance e.g. type of auxiliary products and machinery that can be estimated on the product level. Further, information is needed on the building level regarding intervals for maintenance.

7. Conclusions and Discussion

7.1 Conclusions

A general conclusion that can be drawn based on the information and findings that are presented in this doctoral thesis, and in the papers in the appendices, is that there is a need for further development of LCA methodology to be able to assess both building components and buildings and constructions in an accurate way. The conclusion is based on the need to adopt the structure of performance requirement driven design to be able to accurately define an adequate functional unit for buildings and constructions based on the delivered service. The purpose is to enable assessments of alteration and rebuilding of existing buildings by handling the problem with environmental sunk costs and to define a set of rules to be able to handle economic allocation procedures and the acquisition of accurate economic information as a basis for allocation.

There are several specific conclusions, beyond the general conclusion, that can be drawn based on the presented material. The results of the calculations of emissions generated during the usage phase of a single-family dwellings service life for several different scenarios, based on a variety of different service life durations, technology and societal development scenarios and heating systems, indicate that these have a significant influence on the results of an LCA. The conclusion is that the choice of energy mix and heating system, the service life of the studied building or construction and the assumed development rate have to be parameters that are possible to alter by the user to be able to generate results that are accurate in the actual decision context. It can also be concluded that the choice of life cycle allocation method appears to have a larger influence on the assessment result than the choice of valuation method and the choice of valuation method has a significant influence on the result achieved with a specific allocation method, at least in assessments executed on the material level for multi-recyclable materials as steel. Further, the studies show that the methodological choices regarding boundary setting and the choice of allocation procedures and, to some extent, the valuation has a major influence on the magnitude of the results. The multitude of factors influencing the result of an LCA and the interaction between these factors emphasises the need of a structured procedure for variation analysis to be able to perform a sensitivity check, as recommended in ISO 14043 (ISO, 2000b), in the result interpretation phase of an LCA.

There are two proposals on how to handle allocation in the case of recycling presented in this thesis. Both of the proposals diverge from the ISO 14041 standard recommendations because the methods are proposed to be used if avoiding allocation is not possible and thus disregarding the stepwise procedure that shall be applied according to ISO (ISO, 1998). The first allocation method, the SBI-method ((Anderson & Borg, 1998) and (Borg & Anderson, 1998)), is principally developed to be used in LCAs in the case of recycling that deals with multi-recyclable materials and products. Further, the method is based on two of the principles that are recommended by the ISO 14041 in the case that avoidance of allocation is not possible and these two principles are physical properties and the number of subsequent uses of the recycled material. The method does fulfil several of the criteria for a good allocation procedure presented by Ekvall & Tillman (1997) and by Klöpffer (1996), i.e. the method is easy to apply, even though it requires more information than several other methods available today. Furthermore, it has internal logic, i.e. it does not double account.

The second presented method for open-loop allocation, the economically based method, can be a good alternative for allocation in the case of recycling in the building sector if a consensus for the use of the fictive parallel time perspective and the use of the design factor can be established. These two components will enable us to handle the long service lives of buildings, and the specific characteristics of the same building materials and components built in to different contexts. The two other essential components in the method should not be as hard to establish a consensus about, as the parallel time perspective and the design factor, because there is already an acceptance for the use of economic values as a basis for allocation. Allocation based on economic value is, however, only recommended if the other higher order options in the ISO allocation procedure are not applicable (ISO, 1998). The hierarchy in the ISO procedure can, however, be a topic of discussion. Furthermore, a parallel to finding the appropriate functional unit as a basis for comparative assertions can be drawn regarding the appropriate intermediate product for which the economic value should be established.

The presented method for including an estimation of the usage phase into assessments of building components can be a good method to be used when the requirement of ISO 14025 (ISO, 2000d) that the whole life cycle of a product should be considered in an Environmental Product Declaration (EPD) is to be satisfied. The problem still is, that it is very difficult to establish veritable relationships between the environmental loads generated during the service life of a building and a specific building component, which is the main problem when the usage phase is to be included in building component assessments.

7.2 Discussion

The major part of the LCA methodology development conducted during my doctoral studies and the two case studies on result variation, which are briefly presented in this thesis, is conducted on the material or product level. The relevance of conducting building related environmental assessments on any other level than on the building level has begun to be a topic of discussion. This is mainly because, the building level is considered to be the lowest level on which studies of buildings or building materials and products can be conducted and still provide the necessary information of e.g. location and type of building, to enable an inclusion of the usage phase in the study. Thus, studies on the material level will always be incomplete, as the usage phase usually is omitted due to shortage of information. The inclusion of the usage phase can, however, be handled by applying a context dependent benchmark to represent the actual impact of the usage phase to satisfy the requirements of ISO 14025.

The presentation of the results of the usage phase related energy use in Paragraph 4 indicates that the choice of scenario can influence the result of an LCA in a significant way. The influence of prediction of the service life, regarding both buildings and specific materials and components, will be further emphasised if the construction and demolition of the building and final waste treatment of the employed materials and components are taken into account. The average environmental load per year will be lower, even though the prolonged service life will necessitate additional maintenance.

There are no recommendations regarding which allocation method to use in a specific situation in this thesis, even though two alternative methods are presented. The absence of recommendations is due to the fact that the choice of allocation method/methods, several different methods can be used within a project, is project specific and dependent on several factors. This can be illustrated by presenting some of the factors on which the choice of allocation method will depend. If multi-functional process allocation is addressed, the choice of allocation method will depend on e.g. process characteristics, product characteristics, the goal and scope of the study and the constraints and preconditions of the decision context for which the study is carried out. On the other hand, for allocation in the case of recycling, the choice of method will depend on material characteristics (e.g. recyclability, reusability and waste value) and component or product characteristics (e.g. dismantleability, reusability and predicted service life). The choice can, regarding allocation in the case of recycling, also depend on the LCA-practitioners subjective opinions regarding reasonable time aspects for scenarios concerning recycling processes, material substitution, waste treatment processes, etc. Furthermore, the choice can depend on if it is considered appropriate to use allocation methods for promoting certain behaviour, e.g. the use of recycled materials, or if the main objective of an LCA, and consequently the allocation method, is to reflect reality as accurate as possible. The opinion that the ambition is to reflect reality as accurate as possible is in compliance with the ISO standard because the ISO standard states that the allocation procedure should approximate the fundamental input-output relationships and characteristics that the inventory is based on, as accurate as possible (ISO, 1998).

The conclusion that can be drawn, based on the information presented above, is that there is no point in recommending a specific allocation method but rather in recommending a set of principles and criteria as guidelines, which can be used in the process of choosing an allocation method or methods for a specific project. Examples of guidelines are the ISO allocation procedure presented in ISO 14041 (ISO, 1998) or the stepwise procedure presented in the CSA Guideline Z760, Life Cycle assessment (CSA, 1994). There is, however, a need for rules to be established regarding in which situations allocation principles should be applied. This problem is mainly depending on the scope of the LCA, i.e. if the LCA is for internal or external use and if it is going to be used for product development, product promotion, product benchmarking or environmental declarations.

Product Development

In the case of product development, LCA for internal use, it would be reasonable to assume that the choice of allocation method will be made from the point of view that the result of the study should be as accurate as possible. The objective of delivering a undistorted assessment result will ensure that the chosen allocation method for multi-functional allocation will not be chosen with the purpose to "hide" environmental loads. Therefore, allocation in the case of recycling will not be an issue in the context of product development.

Product Promotion and Product Benchmarking

The choice of allocation methods in the case of product promotion and product benchmarking is a more delicate issue, for multi-functional process as well as for allocation in the case of recycling, than for product development. The main goal when choosing allocation methods in this case is to make sure that the choice is acceptable to all involved parties rather than the most accurate one. The choice should be based on the earlier presented principles (see Paragraph 5), if feasible, and by picking out a method that corresponds with the chosen principles. Furthermore, the goal should be to approximate the reality as accurate as possible and not to fall for the temptation to make the own product better by manipulative use of allocation methods, because this will only lead to scepticism and distrust towards LCA. The risk of manipulative use is nowadays smaller than before due to the requirement of ISO 14040 that an external reviewer, an independent expert, shall review comparative assertions, and LCAs that can be used to support comparative assertions, that will be disclosed to the public.

Environmental Declarations

The data presented in environmental declarations should be as “pure” as possible to enable the use of the information as input in other LCAs in accordance with the goal and scope of that study. One way of achieving this is by applying a well documented and motivated process allocation and to avoid applying any allocation procedure in the case of recycling. The use of this approach will enable the executor of an LCA to choose an allocation method that is in accordance with the goal and scope of that study. This opinion is also presented in the SETAC-EUROPE report on LCA in Building and Construction (SETAC, 2001).

7.3 Further Research Needs

The research conducted within the field of LCA and building and construction that this Doctoral thesis is based on has highlighted several issues of concern for further research. The building industry strives towards a shift in focus regarding how to define the deliverables of the industry from a physical product to a service, e.g. the deliverable of a multi family dwelling project, which has been defined in the design phase by performance requirements, is rather the service of housing than a physical building. This imposes new requirements on the LCA methodology applicable for buildings and constructions. The proposed alterations of the methodology to be able to handle an analysis based on services as the basis for the functional unit, which are presented in **Paper VII**, should be further scrutinised and developed.

The influence of scenarios and the uncertainty introduced by applying scenarios of the future regarding e.g. energy production systems, service life, technology development, maintenance, recycling, substitution etc. should be subject to further research. This will probably lead to further development of LCA tools in the direction of allowing a higher degree of user influence regarding the choice of service life, replacement rates and a larger possibility to alter, for example, the applied energy scenarios.

Another area that could be of interest for further research is to study the increase in environmental loads due to service life prolonging efforts in relation to the, presumably, positive influence on the average environmental load that the prolonged service life will have.

The use of economic parameters as a basis for allocation deserves further research to enable a consensus regarding when to use, what values to use and how to handle scenarios of the future. Furthermore, the concept of environmental sunk costs, in analogy with Life Cycle Costing, to be used in the case of assessments of refurbishment and alteration, should be elaborated further regarding e.g. the compatibility with economic cut-off criteria and other economic parameter based procedures.

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9. Appendices

I **Accounting for the High Recyclability of Steel in LCI and LCA Studies**
Borg, M. & Anderson, J. (1998) Proceedings of the International Conference on Steel in Green Building Construction, Orlando, March 1998.

II **The Influence of Boundary Setting and Allocation Principles on the Results of LCA**
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III **Influence of Allocation and Valuation on LCA Results**
Trinius, W. & Borg, M. (1999) Published in the International Journal of Low Energy and Sustainable Buildings, Vol. 1 1999, Stockholm, April 1999.

IV **Proposal of a Method for Allocation in Building-Related Environmental LCA Based on Economic Parameters**
Borg, M.; Paulsen, J.; Trinius, W. (2001) Published in the International Journal of LCA, Vol.6 No.4 2001, [http://dx.doi.org/10.1065/lca20001.04.051].

V **LCA as decision support in a product choice situation in the building sector – How to take the usage phase into account**
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VI **Energy Production Systems and Related Emissions**
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VII **Generic LCA-methodology applicable for the construction and use of buildings – today's practice and needs for development**
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