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# Life Cycle Assessment for Building Products
## -The significance of the usage phase

**Doctoral Thesis**
**Jacob Paulsen**

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KUNGLIGA TEKNISKA HÖGSKOLAN
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# Preface

In August 1993, I moved from Denmark to Sweden to finish my studies as a civil engineer at the KTH (Royal Institute of Technology). In spring of 1995 I obtained my Master of Science degree with a diploma work in the field of Life Cycle Assessment (LCA) and building materials.

After my MSc thesis, I got an employment at the division for building materials at KTH, where I in the beginning was involved in several projects, not related to this thesis. I also got the opportunity to teach in the topic LCA.

Then, in 1996, I got involved in a project from The Swedish Council for Building Research concerning environmental declarations for building products. The main issue of the project concerned the usage phase for building products when the LCA methodology was applied. Here I got my first ideas about how to deal with the usage phase. Many of those ideas have also been discarded.

In 1997, the MISTRA-project "Sustainable building" then started, and I participated in the topic "LCA and the usage phase for building products". From 1997 to 1999 the main focus of my research has been on a extensive case study on professional maintenance on floor coverings in Sweden. It is this project, which has given the major inputs to this thesis. I took my Licentiate degree in November 1999. Since this, I have developed the ideas about a methodological approach to handle the influence, from building products, on the environmental impacts in the usage phase. In the autumn 2000 I visited Georgia Institute of Technology in Atlanta. There I worked on an inventory of how different material choices can influence the energy use of a whole building. The visit gave me a lot of inspiration to my thesis. During all my work with the thesis I may say that the network with a whole group of Ph.D.- students in the MISTRA-project, all involved in environmental issues in the building sector, have been very valuable for my projects and research environment.
Also, I specially want to thank my colleagues at the Division for Building Material for fruitful discussions and supervision.

## Abstract

Life cycle assessments (LCA) can be used in the building sector to support decision-making on the choice of building products from an environmental point of view. The choice of a specific product can influence the impacts, which occur in the usage phase caused by for example maintenance or energy use. This thesis focuses on the connection between a product choice and the impacts occurring in the usage phase during the service life for the product. The results and conclusions in this thesis are, to a large extend, based on the findings from two larger projects; an inventory concerning maintenance of floor coverings in the Swedish building stock and an inventory of energy use in office buildings. These two projects have given much inspiration to the suggestion of a procedure on how to handle the influence on the usage phase for a building product choice in an LCA perspective. Sources to environmental loads in the usage phase that can be influenced by product choices, are suggested to be divided into four different sources:

1) Emissions from products to the indoor environment.
2) Emissions from products to the outdoor environment, e.g. leaching of hazardous substances.
3) Interference with the resource flows in building systems, e.g. energy use.
4) Consumption of auxiliary products and resources for maintenance, e.g. cleaning or painting.

For maintenance and operational energy, it has been shown that the magnitude of the environmental loads in the usage phase, influenced by a product choice, can be very significant compared to the rest of the product life cycle. The suggested procedure consists of two steps. The first step is to assess if the influence on environmental loads in the usage phase can be relevant to consider for the actual type of building product. The second step is to assess the possibility to estimate these environmental loads from the usage phase if they have been found relevant in step one.

One major conclusion of this work is that several building specific data is needed on the building level to estimate the magnitude of environmental loads from the usage phase. With knowledge only about the product, the magnitude of the environmental loads from the usage phase cannot be estimated. However, in the planning and construction phase, the building specific data should be possible to collect and, thereby, make it possible to include the significance of the usage phase in an LCA-supported decision process. To do so, a model for estimating the impacts is needed. The model can be an analysis-tool with three types of data:

1) Life Cycle Inventory-data for the flows in the usage phase (like energy, maintenance products or product emissions).
2) Life Cycle Inventory-data for the actual building products.
3) Building specific data (like expected service life and maintenance intervals).



**Keywords**: Building Products, Energy Use, Environmental Loads, Floor Coverings, Life Cycle Assessment, Maintenance, Service Life, Usage Phase.

## List of papers

This PhD thesis is based on the following publications:

1) Borg, M. and Paulsen, J., 2000: *Proposal of a Method for Allocation in Environmental LCA Based on Economic Parameters*, Pre-print June 2000, Published in the International Journal of Life Cycle Assessment (20th April 2001).[http://dx.doi.org/10.1065/lca2001.04.051].

2) Paulsen, J.,1998: *Life cycle impact of floor coverings -A model for the contribution of the usage phase*. Proceedings of the international CIB conference, Construction and the environment, 7-12 June 1998, Gävle, Sweden.

3) Paulsen, J., 1999:*Service life prediction for floor coverings*, Proceedings of the international 8dbmc conference in Vancouver 31.maj-3.juni 1999.

4) Paulsen, J.; 2001: *On the significance of the usage phase in an LCA - Application o floor coverings,* Pre-print April 2001, Submitted to the International Journal of Life Cycle Assessment (20th March 2001).

5) Paulsen, J. and Augenbroe, G., 2001: *The role of energy use predictions in the choice of building materials*, Pre-print February 2001, Submitted to the International Journal of Low Energy and Sustainable Buildings (14th February 2001).

6) Paulsen, J. and Borg, M., 2000: *LCA as decision support in a product choice situation in the building sector -How to take the usage phase into account*, Pre-print December 2000, Submitted to the International Journal of Life Cycle Assessment (13th December 2000).

# Table of content

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# 1 Introduction

## 1.1 Sustainable development and the building sector

Sustainable development was defined in the Brundtland Report 1987 as a "development that meets the needs of the present without compromising the ability of future generations to meet their own needs". The pursuit of sustainable development places the building sector into focus because the building industry strongly influences the environment. As an example, in the European Union, buildings are responsible for more than 40% of the total energy use and the construction sector is estimated to generate approximately 40% of all man-made wastes. (CIB, 1999). One element in moving towards a sustainable development in the building sector is to reduce the use of resources for a desired product or services. The idea is known from the "Factor 10 club" where it is realised that the global use of resources has to be reduced with a factor 10 in the near future, still providing the same services. The scenario is that the standard of living has to be as in the industrial countries, the population will increase to 10 billion people and the resources shall be distributed in a fair way between the population of the world. To reduce the resource use per service unit in the building sector, several approaches can be used. However, assessment of environmental impacts in the building sector is a quite complex and difficult task. When it comes to assessments of how building products influences the environment, an improvement in one area of the product life cycle can lead to an unwanted impact in another area of the product life cycle. It is, therefore, of outmost importance to have a comprehensive view over the whole sphere, which is influenced by an intended action or product choice for environmental improvements. In that context, Life Cycle Assessment (LCA) has shown to be a powerful tool to compare several products concerning their environmental performance. However, it seems as several obstacles occur when the LCA-methodology is applied to assess how building products influence the environment. Building products have a relative long service life and many actors involved during the product life cycle which makes it difficult to predicting what actually happens during the life cycle, especially in the usage phase. It is therefore desirable with a further development of the LCA methodology to more systematically take into account the influence of the usage phase in a building product choice.

## 1.2 Structure of this thesis

This thesis focuses primarily on the usage phase of building products and how the choice of a specific product influences the environmental impacts in the usage phase. The results and conclusions in this thesis are to a large extend based on the findings from two larger projects; an inventory concerning maintenance of floor coverings in the Swedish building stock and an inventory of energy use in office buildings. Further, an economical based allocation procedure for long-lived building products is shortly discussed.

**Chapter 2** gives an introduction to the LCA-methodology with focus on aspects concerning the usage phase for products.

**Chapter 3** gives a survey over the use of LCA for building products and the obstacles occurring because of the structure of the building sector. The focus is on the usage phase and why impacts from this stage can be hard to handle. A procedure for economical allocation is also briefly discussed based on findings in Paper 1.

**Chapter 4** deals with the topic "maintenance of building products". Findings from Paper 2 and Paper 4 are discussed which concerns maintenance of floor coverings. It is here shown that the impacts from the usage phase can be significant compared to the production process and depending on the actual material choice. The estimation on service life for floor coverings is also shortly discussed based on findings from Paper 3.

**Chapter 5** deals with the findings from Paper 5 concerning the energy use for office buildings and how sensitive the energy balance is to even small changes in materials and material parameters.

**Chapter 6** gives a suggestion how to deal with the usage phase in a Life Cycle Assessment of building products. This Chapter is based on the findings from Chapter 3,4 and 5 and Paper 6. Paper 6 is a suggestion on where to detect impacts in the usage phase related to specific choices of building products. Furthermore, a suggestion is given on how to handle the usage phase in a methodological way.

**Chapter 7** is a discussion of the whole thesis.

**Chapter 8** contains conclusions and further research needs.

The content of this thesis is to a large extent based on my work and participation in the following projects:

| | |
|---|---|
| MISTRA Sustainable building: | "LCA Methodology for Sustainable Building -LCA in the Usage Phase" |
| Swedish Building Research Council: | "LCA-studies of entire buildings" |
| SETAC-Europe | "LCA in building and construction Subgroup topic: LCI-data |

# 2 Life Cycle Assessment

## 2.1 Introduction to LCA

In the following a brief description of Life Cycle Assessment (LCA) is given to support the understanding of methodological problems, that occur when assessing and/or analysing products in the building sector. The method is to a large extent described and further developed by SETAC, (Fava et al, 1990), (Consoli et al, 1993), CML (Heijungs et al, 1992), Nord (Lindfors et al 1995), IPU (Hauschild & Wenzel, 1998), LCANET (Frischknecht et al, 1997). Also, the method is defined by the ISO 14000 series ISO 14040 (ISO 1997), ISO 14041 (ISO 1998a), ISO 14042 (ISO 2000a) and ISO 14043 (ISO 2000b). The following description of LCA is based on the sources mentioned above, together with my own experience in the field.

LCA is a method or tool to assess the potential environmental impacts of a product or service in a quantitative way. The concept "Life cycle" incorporates an expansion both temporal and spatial compared to the product or service. The temporal expansion means that the product or service analysed is followed "from cradle to grave". The cradle can normally be the extraction of raw material and fuel to produce the product analysed (or product to provide a service). The cradle can be defined as the place or moment when the raw materials or resources are taken from nature into the technical system. In the same way, the grave can be defined as the place and time when the products or used resources are returned to nature. The spatial expansion means that also transports, production facilities, auxiliary materials, supplying systems, maintenance, waste treatment and similar activities necessary for the whole life cycle have to be included to the analysis. The environmental potential impacts consider resource use, human health, and ecological consequences.

## 2.2 Use of LCA

According to the international standard ISO 14040 an LCA can assist in

- identifying opportunities to improve the environmental aspects of products at various points in their life cycle;

- decision-making in industry, governmental or non-governmental organisations (e.g. strategic planning, priority-setting, product or process design or redesign);

- selection of relevant indicators of environmental performance, including measurement-techniques;

- marketing (e.g. an environmental claim, ecolabelling scheme or environmental product declaration).

## 2.3 Phases of an LCA

The LCA is divided into 4 phases:

1) Goal and scope definition
2) Inventory analysis
3) Impact assessment
4) Interpretation

As illustrated in Figure 1, the LCA is an iterative process. During the process, adjustments can be needed compared to the original assumptions. Thereby, it can be necessary to iterate between the four phases during the progress of an LCA.

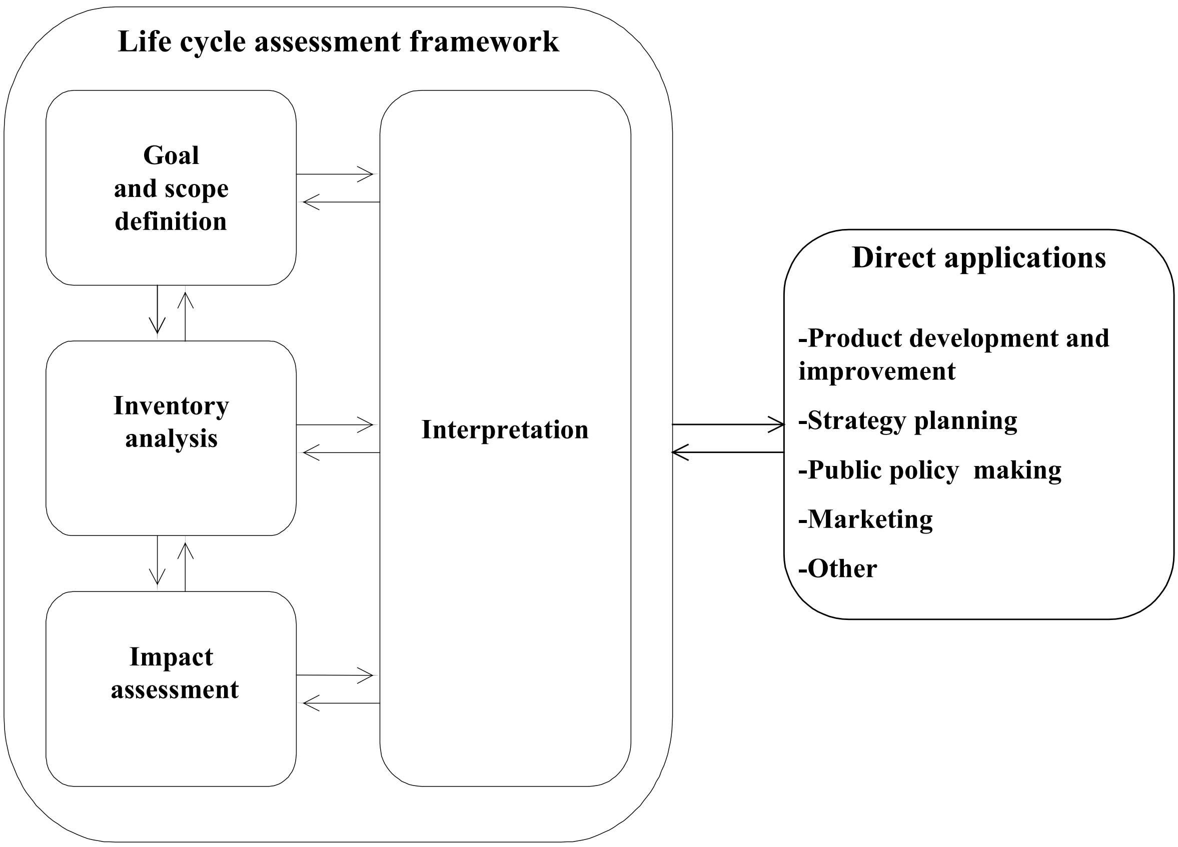



**Figure 1. The four phases of an LCA (ISO 1997).**

### *2.3.1 Goal and scope definition*

The goal and scope definition is the first step in LCA. It is a prerequisite that the performance of an LCA is consistent with the goal and scope definition. When performing LCA, a transformation of reality into a modelled system has to be done. The system modelling can be done in several ways. When performing an LCA for one or several products there is a large degree of freedom in modelling the system. It is stated that the choice of elements of the physical system to be modelled is dependent on the definition of the goal and scope of the study. One consequence is that input and output that will not significantly change the overall conclusions do not have to be estimated. It is, however, also stated that any decision to omit life cycle stages, processes or inputs/outputs shall be clearly stated and justified. Therefore, a well-defined goal is needed to motivate the choice of the most suitable system boundaries, allocation procedures, quality demands on data, choice of environmental indicators and also definition of the functional unit. Thereby, the results from the actual LCA are only valid for the defined goal and scope. However, it often appears that the goal and/or scope has to be revised during the analysis, for example caused by lack of data, important findings or similar, hence leading to LCA being iterative in its procedure.

Functional unit

The functional unit has to be defined in the goal and scope definition phase. One of the primary purposes of a functional unit is to provide a reference to which the input and output data are related. Therefore, the functional unit has to be clearly defined and measurable. The amount of product, necessary for fulfilling the function, must be able to be quantified and is thereby the basis for the analysis. The flows related to the functional unit are then used to calculate the inputs and outputs of the system. Comparisons between systems are made on the basis of the same function, and quantified by the same functional unit. The bottom line of this definition is that it is the performance/service of a product, which has to be comparable to the service/performance of another product, not to the product itself. When comparing different products, even the different product systems have to be comparable. A painted surface can serve as an example: It is no use to compare one litre of painting with one litre of another type of painting because they do not necessarily deliver the same performance. The functional unit "one square metre of painted surface with a particular degree of coating and a service life of 10 years" could be suitable as a functional unit.

System boundaries

Product systems are subdivided into a set of unit processes. The system boundaries define the unit processes to be included in the system modelled. The product system should be modelled in such a manner that inputs and outputs at their boundaries are elementary flows, which are linked to unit processes.

Allocation procedures

Allocation in LCA is defined as "Partitioning the input or output flows of a unit process to the product system under focus". When input or output flows can be partitioned in several ways e.g. between unit processes, a motivated principle is needed for how to allocate the flows. Several allocation principles are developed, based on different principles (e.g. mass balance, economical values).

### 2.3.2 Inventory analysis

A life cycle inventory analysis is concerned with the data collection and calculation procedures. The modelled system, defined in the goal and scope definition, is transformed into a process tree or flow diagram. Every activity in the process tree is divided into unit processes, the smallest unit in an LCA. Every unit process is connected with input and output, see Figure 2. Data is collected and evaluated with respect to the requirements defined in the goal and scope. Then, the data is related to each unit process and afterwards related to the functional unit. With these relations, it is possible to aggregate the data for each process, according to the functional unit. During the inventory analysis, it can be necessary to refine the system boundaries (and in some cases the goal) because of lack of data, or as a result from a sensitivity analysis, see Figure 1. The result obtained so far is called a Life Cycle Inventory (LCI) and serves as input to the following impact assessment. In some cases conclusions can be drawn directly from the LCI (if stated in the goal and scope), but the results have to be interpreted with caution because they refer to input and output data and not to environmental impacts.

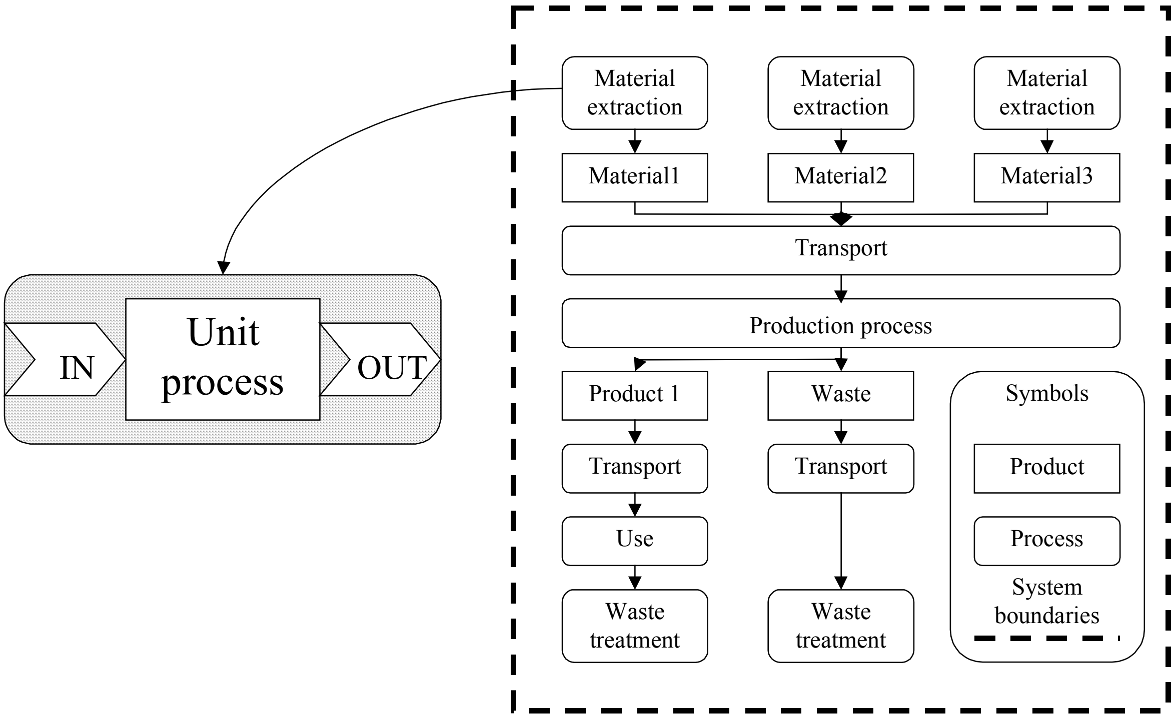



**Figure 2. Process tree consisting of unit processes (Paulsen 1999a).**

### 2.3.3 Life cycle impact assessment

Life Cycle Impact Assessment (LCIA) is the third phase of life cycle assessment. The purpose of LCIA is to assess the life cycle inventory (LCI) results from the product systems, to better understand their environmental significance. In the LCIA phase selected environmental issues, called impact categories, are modelled, and category indicators are used to condense and explain the LCI results. Category indicators are intended to reflect the aggregated emissions or resource use for each impact category. These category indicators represent the “potential environmental impacts”. In addition, LCIA prepares for the life cycle interpretation phase. The LCIA can be divided into two main steps (see Figure 3). The first step contains three phases to produce a LCIA profile. The second step is optional and a further elaboration of the LCIA profile to create an aggregated value of the environmental impacts.

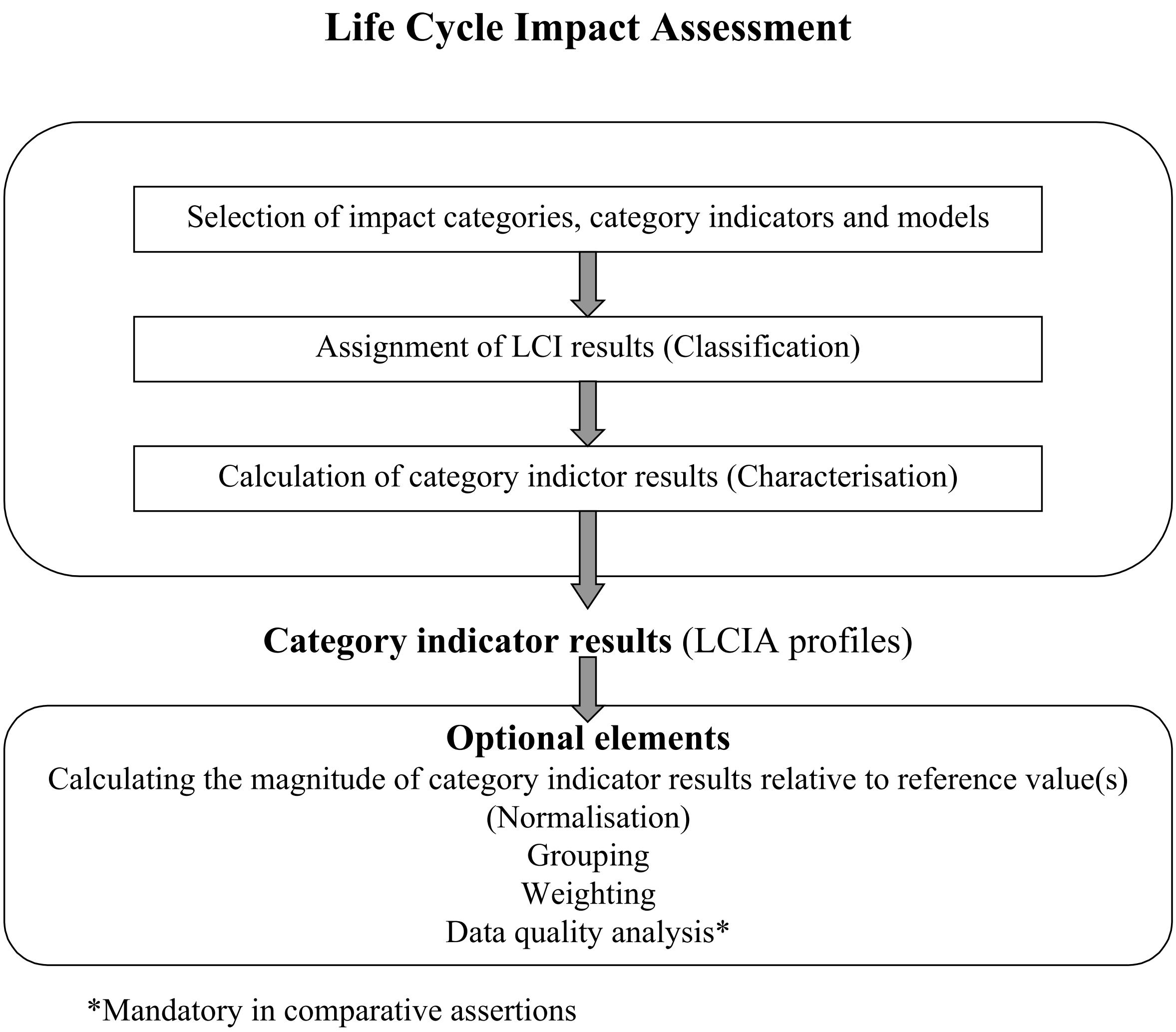



**Figure 3. Elements in an LCIA (ISO 2000a).**

Selection of impact categories

The first element of the LCIA concerns the choice of impact categories and category indicators. The choices have to be appropriate to the goal and scope of the study. A list of impact categories is suggested in Nordic Guidelines (Lindfors et al, 1995). In Figure 4 the concept of indicators is illustrated. As an example, acidification is chosen as an impact category. The category indicator is then proton release ($H^+$). The category endpoint can be forest, vegetation, etc, but here models are needed to estimate the environmental effects at the endpoint. The success and relevance of this estimation depend on a lot of factors. Depending on the goal, scope, quality and quantity of data etc, the category indicator can be chosen anywhere between the LCI and the category endpoint.

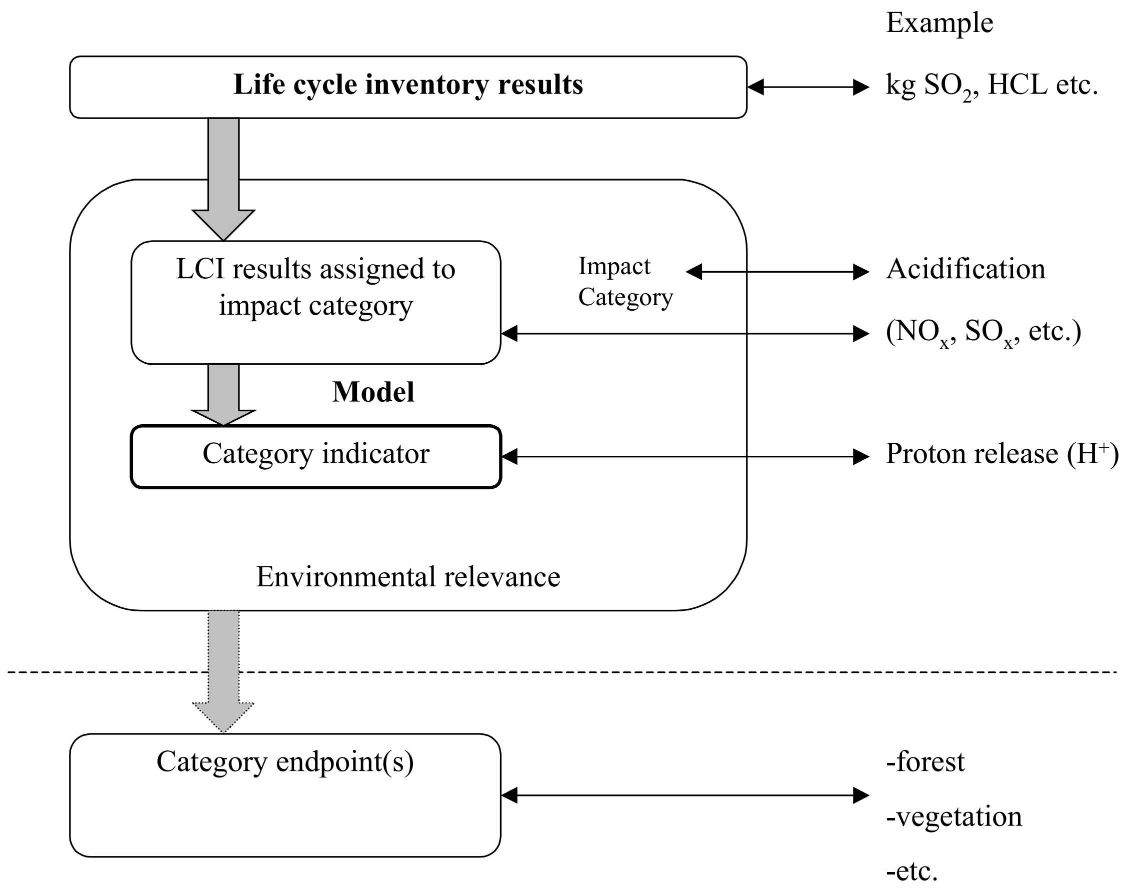



**Figure 4. Concept of indicators (ISO 2000a).**

The choice of impact categories should be indicated as early as in the goal and scope. However, when the LCI is carried out, it can become necessary to redefine the goal and scope. The LCI can indicate that a new priority of impact categories seems motivated. Also, lack of information can make it impossible to use certain impact categories. This illustrates the iterative nature of LCA.

Classification

Classification is a procedure to assign the LCI results to the chosen impact categories. Actually, this stage is only a rearrangement of the data from the LCI with two exceptions:

1) Some of the input and output data from the LCI cannot be placed in any of the chosen impact categories. Thereby, they are omitted in the rest the analysis if not a redefining of goal and scope is done concerning the choice of impact categories.
2) Some of the input and output data from the LCI can be placed in more than one impact category and, thereby, double accounted for. Following the guidelines, this is allowed as long as the categories do not contribute to the same cause-effect-chain.

Characterisation

Characterisation is here a synonym for calculation of the category indicator. All the parameters in the different impact categories need to be multiplied with an equivalency factor to estimate their contribution to the impact category. In that way, each impact category can be presented as a one-dimensional numerical indicator, which is the final result of an LCIA.

Optional elements

The result from the LCIA can be further elaborated by e.g. normalisation, grouping or weighting. Normalisation is to calculate the magnitude of the category indicator results, relative to reference values. Also the impact categories can be sorted and/or ranked by grouping. Finally, the category indicators can be converted into one-dimensional value, using numerical factors based on value choices. All the above mentioned elements are dependent on (and have to be consistent with) the goal and scope definition.

### *2.3.4 Interpretation*

The interpretation of the LCIA depends on the goal and scope of the analysis. Earlier this stage was called “improvement assessment” but has lately been changed to “interpretation” due to the fact that the goal and scope not necessarily require an improvement assessment. In the interpretation of the result, the whole analysis has to be discussed, regarding data quality, scope and boundary settings, validity of the study and sensitivity of results.

# 3 LCA and the usage phase for building products

The LCA-methodology has developed rapidly during the recent years. The technique is to a large extent used and developed for environmental assessments of short life products from industrial sectors such as packaging. LCAs are used for assessment of materials and components either for the purpose of comparing different alternatives or for proposing improvements. The methodologies have, to a large extent, been adopted by the building sector and have given much valuable input. But, some obvious distinguishing properties of building materials and components, compared to most other industrial products, are their significantly longer service life and the lack of information concerning the influence on the environmental impacts in the usage phase. Especially the usage phase might show to be of major importance in the building sector from an environmental point of view, because of the long service life.

A number of LCAs have already been carried out on long-life products from the building sector, despite the problems with lack of information concerning the usage phase, e.g. (Erlandsson et al 1994, Jönsson 1995, Erlandsson 1995). In general, two different methods have been used to circumvent the problems. It has either been assumed that the products influence on the environmental impact in the usage phase is zero (not depending on the choice of material/product). Or a comparative analysis has been carried out with the assumption that the influence on environmental impacts in the usage phase is the same for the analysed products. In this case, the impacts from the usage phase level out each other. As will be argued later in this Chapter, omitting the influence on the usage phase in a comparative LCA for a building product, could possibly lead to a sub-optimisation from an environmental point of view.

## 3.1 System levels

When an LCA is carried out for a building product, the whole life cycle has to be considered. In Figure 5, a schematic illustration is given over the life cycle for an unspecified building product. The life cycle is divided into 6 stages, which are placed in 4 different system levels. The LCA-stages are related to chronological life stages of the product. The system level, regards the complexity of the structure in which the product participates. The actors influencing the impacts from the product (related to the functional unit) vary during the life cycle stages.

<u>Extraction of raw materials (system level 1)</u>

The life cycle of the building product normally starts with extraction of raw materials followed by a preparation into a building material. The degree of preparation can vary broadly. In most cases the product is send forward to a producer of building materials or components, but in some cases, the raw materials are used directly on the construction side.

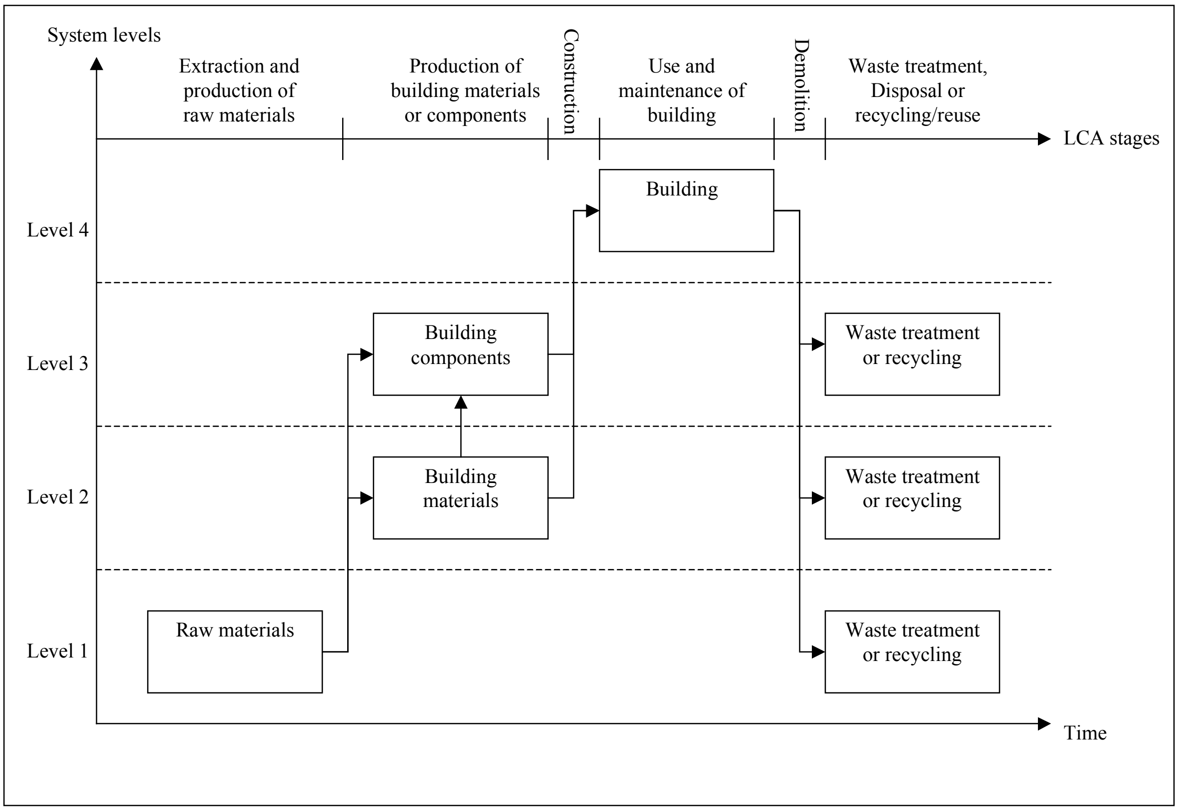



**Figure 5. System levels in a building products life cycle (Paulsen 1999a).**

Production of building materials or components (system levels 2 and 3)

The raw materials from the first LCA stage are normally converted into building materials or more complex products like building components or parts. Depending on product type this can be regarded as system level 2 or 3.

Construction

In the construction phase, the building products are applied to a whole building. This means that all the products are raised from system level 1,2 or 3 up to level 4. The product starts to serve as (or as a part of) a function and can be related to a "functional unit".

Use and maintenance of buildings (system level 4)

In this phase, the building products are incorporated in a more complex system, a building. The environmental impacts from a functional unit (performed mainly by a building product) in this stage, depend on several factors other than the building product chosen for the actual function. Important factors are here e.g. type and methods for maintenance together with intervals for maintenance and replacement.

Demolition

The demolition of a building indicates the end of a functional unit preserved by a building product. The functional unit is transformed back to a product, with or without a residual value.

Waste treatment, Disposal or recycling/reuse (system level 1-3)

After the demolition, the outcome can be treated in different ways either as waste or reused/recycled in new applications. Depending on the fate of the product, the system level can be regarded as between 1 and 3.

Two-level model

A simplification can be done regarding Figure 5, to highlight the obstacles of the LCA methodology regarding building products. A product life cycle can be divided into three steps:

1) Before installation of the product in a building.
2) During the usage phase in a building.
3) After the product is removed from the building (e.g. demolition).

Thereby, the system levels can be divided into two superior system levels:

1) Building level, a product provides a function, eventually supplied by other products (e.g. maintenance).
2) Product level, before or after the usage phase for the product. The product does not provide any function in these stages.

## 3.2 The functional unit for building products

The LCA methodology can be used in the building sector to support decision making for a choice between different building product. When the LCA methodology is used for comparison, two issues are important to remember:

1) LCA regards the whole life cycle, from cradle to grave.
2) It is the function/service, which creates the basis for comparison, not the product itself.

Combined with the information about system levels, see Chapter 3.1, some obstacles occur when it is desired to carry out an LCA for a building product. As stated earlier, the product does not provide a functional unit on a lower system level. First when the product application in the building is known, the functional unit can be created. Actually, that means that it is impossible to carry out an LCA for a product, taking the whole life cycle into account, unless the application is known (construction stage). Furthermore, knowledge is needed concerning all the impacts related to the use of the function during its service life (usage phase), the expected service life (usage phase) and the impacts from the demolition phase (waste treatment phase).

The producer of a building product can be expected to have good knowledge of the first steps in the product lifecycle concerning raw material extraction and the production process. When it comes to the construction phase, several application possibilities can exist for the product to obtain different functions. Even if the application possibilities can be limited to a reasonable number, the impacts from the usage phase can vary broadly caused by external parameters. As an example, the maintenance of a façade can be strongly dependent on the exposure to weather as well as to aesthetic demands.

## 3.3 Connection between choice of building product and impacts in the usage phase

As stated above, the usage phase is difficult to handle for building products in general. The building products participate in a so-called functional unit where important LCA information does not exist before the construction phase. Besides, a lot of the impacts from the usage phase are related to services, which cannot be connected to the choice of building products. In Figure 6, a suggestion is given for how to divide the life cycle into 4 parts. The first and last part, which normally are included in a building product LCA, are delimited by the two dotted lines. The usage phase is between the dotted lines. As showed the impacts from the usage phase are divided into two different parts. The left part of the usage phase, see Figure 6, symbolise all the impacts, which are not influenced by the choice of the analysed building product. However, it is also suggested that in several cases there are impacts, which are influenced by the choice of the analysed building product (the right part of the usage phase in Figure 6).

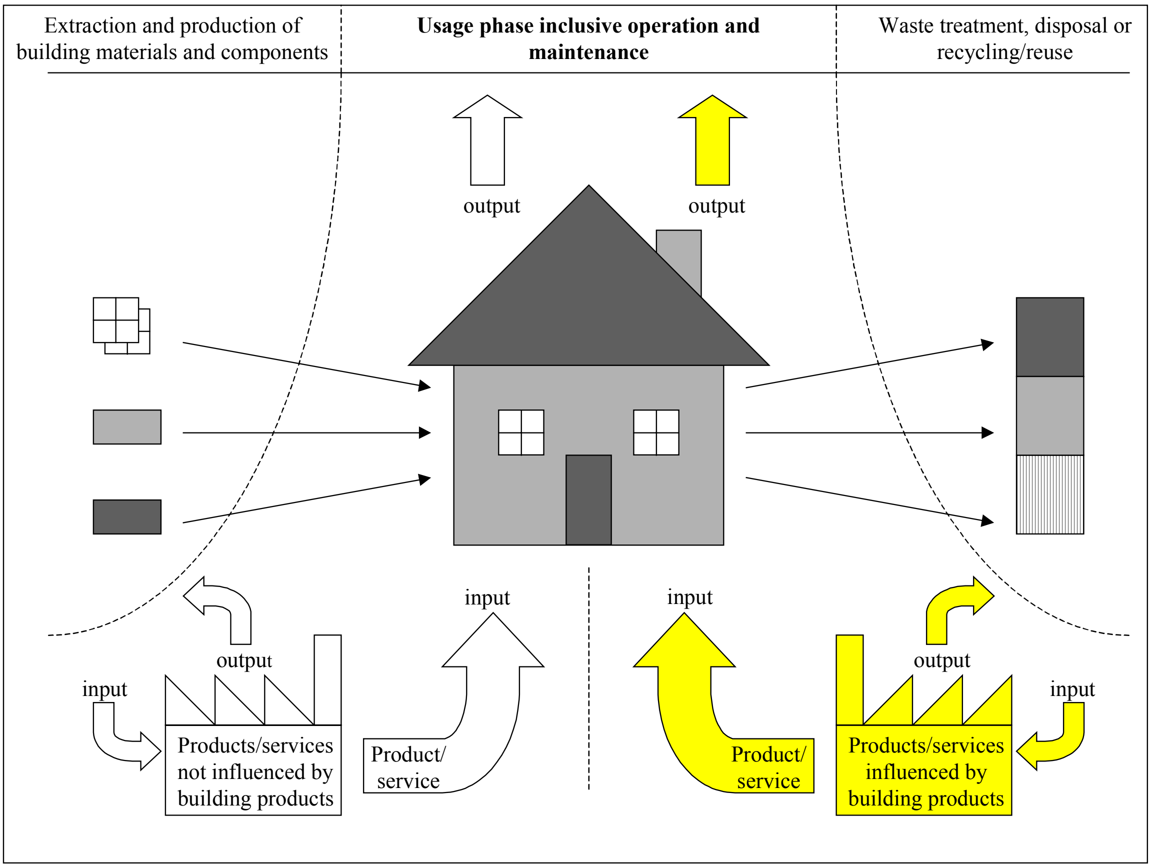



**Figure 6. Impacts from the usage phase related to building products (Paulsen 1999a).**

To compare different products for the same function, the LCA methodology can be used to get the opportunity to optimise the choice in an environmental point of view. However, if the usage phase is not regarded, it can turn out to be a sub-optimisation. This is explained by the fact that some of the impacts from the usage phase are influenced by the building product choice in the construction phase, even if these impacts can be very hard to estimate. To optimise the choice of building products, the influence on the impacts from the usage phase have to be estimated in some way. It does not seem to be sufficient with the impacts from the first and the last stages of the life cycle, unless it can be stated that the impacts from the usage phase are insignificant or not influenced by the choice of the actual building product.

To develop a procedure for handling the usage phase for a building product in an environmental point of view, several case studies and inventories have been carried out. Partly to inventory the possibility to handle the usage phase and partly to get an idea of the magnitude of the impacts from the usage phase for some types of products. Chapter 4 of this thesis deals with the findings from an extensive inventory of maintenance of floor covering where the impacts in the usage phase are connected to the use of resources for maintenance. Chapter 5 deals with how material choices on product level can influence the energy use in the usage phase of a whole building over the service life.

### 3.4 Allocation procedures for LCA on long lived building products (Paper 1)

During my work with the usage phase, I was involved in a proposal for an allocation procedure based on economic parameters, see Paper 1. Allocation procedures are not directly related to the rest of the thesis, which is focused on the usage phase. However, when the LCA methodology is applied to building products, their long service life does also influence the choice of allocation procedures as well as the problem with handling the usage phase. The choice of allocation procedure can be very important for the result variations as shown in e.g. Trinius and Borg, 1998a,b. The proposed method in Paper 1 shall be seen as a contribution to the already existing group of different allocation methods and will only be handled in this sub section. The method is addressed to long lived materials with a high recyclability and an expected economic residue value at the end of the product life cycle (e.g. open loop recycling of different types of metals).

Shortly described the proposed method is based on three principles:

1) 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 Waste Fraction (WF) and the Recycled Fraction (RF).

3) The quality reduction between the materials in two following product life cycles is indicated by the ratio between the market value for the material in the products.

A simplification for the model in Paper 1 is shown in Figure 7 and by Equations (1) and (2) below where:

| | |
|---|---|
| WF | is the waste fraction of the virgin material in the succeeding recycling process. |
| RF | is the recycled fraction of the virgin material in the succeeding recycling process. |
| V0 | symbolise the un-extracted virgin raw material. |
| VF | symbolise the upgraded virgin raw material, ready to use in a given application. |
| SF | is the market value of the upgraded virgin raw material VF. |
| $L_{V0 \rightarrow VF}$ | are the environmental loads for the upgrading of V0 into VF. |
| R0 | symbolise the untreated virgin raw material after use, which are going to be recycled. |
| RG | symbolise the upgraded raw material R0, ready to use in a given application, comparable to the application of VF. |
| TG | is the market value of the upgraded recycled raw material RG. |
| $L_{R0 \rightarrow RG}$ | are the environmental loads for the upgrading of R0 into RG. |
| $L_{forward}$ | are the loads from material VF, which is distributed forwards to material RG. |
| $L_{backward}$ | are the loads from material RG, which is distributed backwards to material VF. |

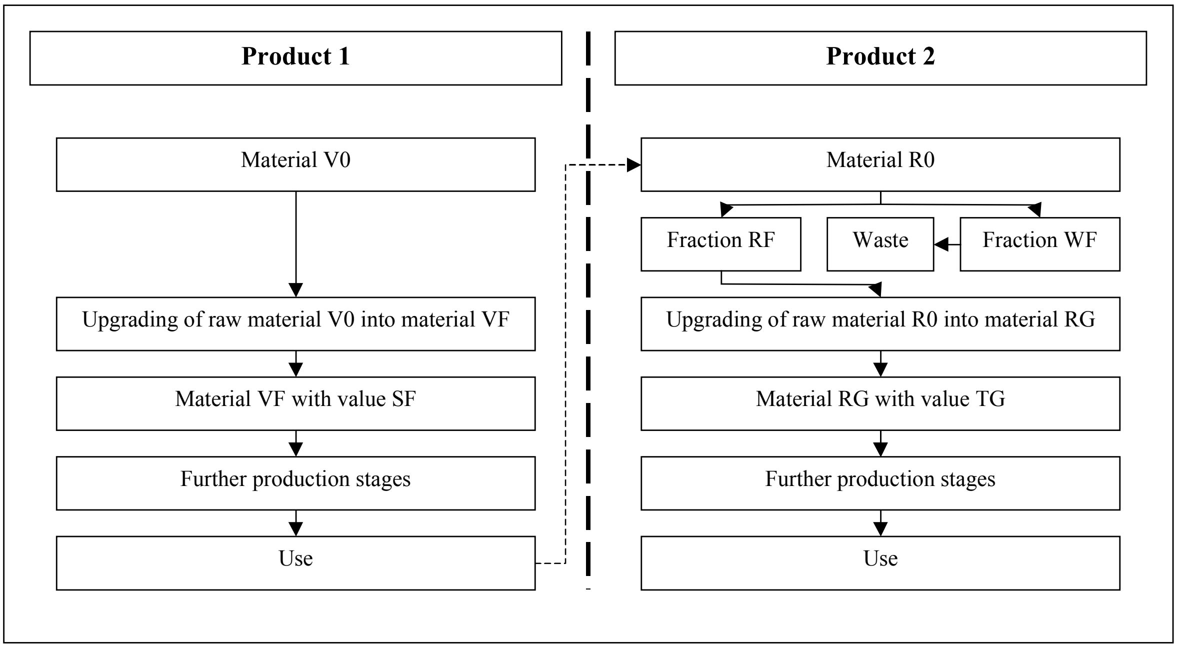



**Figure 7. Production processes for virgin and recycled materials in products.**

Material VF is a virgin produced material with market value SF and the impacts from the production of material VF is $L_{V0\rightarrow VF}$. RF is the expected fraction of recycled material, estimated through a so-called design factor. WF is the waste fraction (RF+WF=1). The recycled material is called RG with the market value TG and impacts from the recycling are $L_{R0\rightarrow RG}$. The recycled material RG has to be comparable (concerning the usability) to material VF. Then the parts allocated forwards and backwards can be expressed as in Equations (1) and (2) respectively:

$$L_{forward} = RF \times L_{V0\rightarrow VF} \times \frac{TG}{SF} \qquad (1)$$

$$L_{backward} = RF \times L_{R0\rightarrow RG} \qquad (2)$$

The feasibility with the proposed allocation procedure is that an approximation for the ratio TG/SF can be done using today's market values for virgin and recycled materials. It is argued for and assumed in Paper 1 that the ratio TG/SF probably will vary less than several other possible allocation parameters during the long time perspective and thereby be a useful parameter for estimating allocation ratios.

# 4 LCA case studies on the maintenance of floor coverings

To develop the LCA methodology with focus on the maintenance of building products, a comprehensive inventory has been carried out concerning floor coverings. The reason for choosing floor coverings were:

1) Several LCAs already exist for floor coverings with focus on the production and the waste treatment (the usage phase is omitted).
2) The usage phase for floor coverings can be expected to have a significant impact because of short maintenance intervals.

The focus has been on the external environment. The indoor environment, work environment or other aspects on the building level, where the floor coverings possibly could influence the function of the whole building, have not been considered. The first step in the case study was to suggest a systematical approach for an LCA- inventory, valid for floor coverings in general.

## 4.1 Methodological approach (Paper 2)

As a preparation for the inventory of maintenance of floor coverings a first approach on how to proceed and some preliminary finding have been recorded in Paper 2 (Paulsen, 1998). The possibility to analyse the usage phase for floor coverings in a methodical way was found to depends on the possibility to create a model for the maintenance by generalising:

1) The cleaning and maintenance methods.
2) The products and machinery used for maintenance.
3) The amount of products and resources used for each maintenance method.

Furthermore, the possibility to analyse the usage phase was found depending on the possibility to create LCI-profiles for the groups of maintenance products, machinery and other products used for the maintenance. The creation of a model was also started here and primary three findings were done. First, the maintenance could be divided into 3 main parts, see Table 1.

*Table 1. Symbols and example of intervals for three types of maintenance.*

| Parameter | Symbol | Frequency (examples) |
|---|---|---|
| Frequent maintenance | F | 1-7 times at week |
| Periodical maintenance | P | 0,25-2 times at year |
| Upgrading maintenance | U | 0-1 times during the service life years |

Different methods, products and amounts of resources are used in these three types of maintenance and it was therefore found necessary to take this into account in a future model. Further, it was found necessary to restrict the inventory to professional maintenance. Thereby it should be possible to decrease the number of products and methods to a manageable number.

Finally, it was found the maintenance could be regarded as constant over time for each of the three different types of maintenance. It was argued by the cleaning industry that a proper and well-done periodical maintenance protects the floor surface against wear.

## 4.2 Service life prediction (Paper 3)

An important parameter in the LCA of floor coverings is the prediction of the service life, because the environmental loads per year caused by the production stage is inversely proportional to the service life. This topic has been paid special attention in Paper 3 (Paulsen, 1999c). The conclusion regarding floor coverings in the public and service sector in Sweden is that generalising of the service life is impossible only considering the type of floor covering. However, with additional information about the type of premise where the floor covering is or will be installed, it should be possible to detect the type of service life, which gives the actual service life. In Figure 8 the model for service life is illustrated.

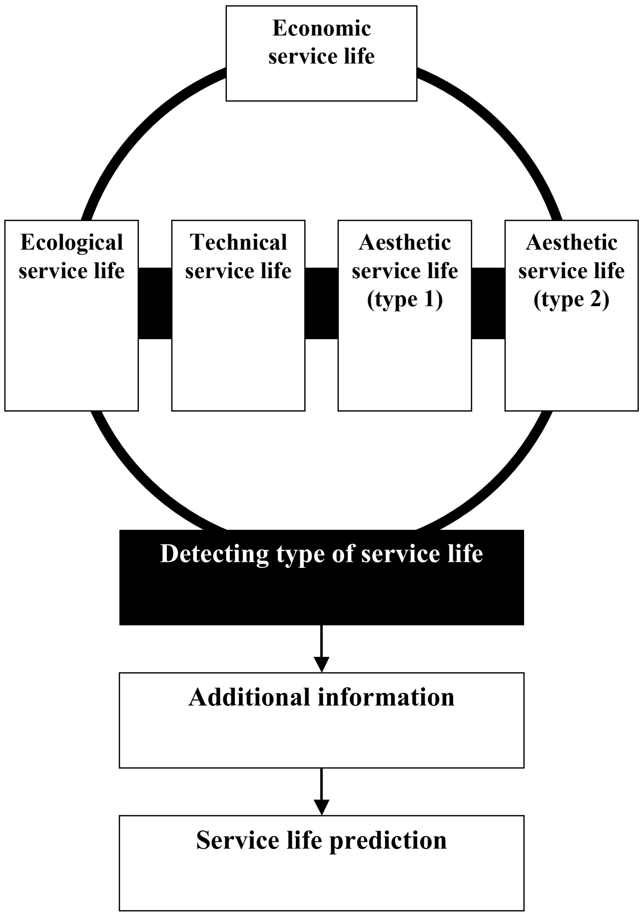



**Figure 8. Service life prediction for floor coverings (Paulsen 1999a).**

As illustrated in Figure 8, it would not be very feasible to connect the service life directly to the technical service life. Rather, it would be more feasible to first detect which factors influence the service life in the actual type of premise. This conclusion has led to variable choice of service life parameter in the inventory of maintenance of floor coverings, presented in Paulsen 1999b and Paper 4.

### 4.3 Findings from the inventory of maintenance of floor coverings (Paper 4)

The inventory concerns the Swedish building stock and is fully described in (Paulsen 1999b). In Paper 4, an extraction of the main findings is given. The findings from Paper 2 and 3 were used to guide the inventory. One of the first limitations in the inventory was to restrict the study to floors maintained by professional cleaning companies. This area is approximately 150 million square meters from which 60% (approximately 90 million square meters) showed to be linoleum or PVC-flooring. This was a necessary limitation to make it possible to generalise the maintenance methods. After a dialogue with the leading cleaning companies in Sweden it seemed reasonable to restrict the cleaning methods into thirteen different cleaning systems. However, the cleaning systems did only represent the frequent maintenance. For the periodical maintenance, two methods for linoleum flooring and three types for PVC-flooring were identified as common for the professional cleaning sector. The upgrading maintenance was found to be insignificant. The professional cleaning is located to the public and service sector together with the rental non-residential floor area. Even though the methods for periodical and frequent cleaning seemed reasonable to restrict to five and thirteen different methods respectively, a huge range of different products are used even for the same methods. Thus, after several meetings with different cleaning companies and the branch organisation for production of cleaning agents, it even seemed reasonable to restrict the cleaning agents to a few main types with an average LCI-profile for each product type. For the machinery three different machines were selected and analysed. In co-operation with two of the leading cleaning companies in Sweden, it was found that two scrubber-drier machines, a small and a large, could be seen as representative for the machines used in Sweden. Only one polishing machine was selected to be analysed, but also this one could be seen as representative for the Swedish cleaning companies. In this stage it was obvious that the number of different combinations of periodical and frequent cleaning together with different intervals for cleaning were heavily exceeding the number expected from the beginning of the inventory. A calculation and analysing tool were developed containing an LCI database with data on all the used products and resources. For each maintenance method (both frequent and periodical), a reference unit was created referring to one occurrence of maintenance for one square meter of floor covering. Because of the many possible ways to maintain a floor covering, these reference units could then be combined to create a suitable functional unit.

Not all the methods for frequent and periodical maintenance were compatible. The number of relevant combinations was 36 different maintenance methods. For some of the methods, the use of warm water gave a significant contribution to the energy use. After a discussion with some of the actors in the cleaning sector, it seemed doubtful to assume that the water used for cleaning always was warmed up. For some of the newer cleaning agents it is recommended that cold water is used. In the calculation program the temperature can be varied. As other variable parameters the frequency for frequent maintenance (e.g. times per week), the frequency for periodical maintenance (e.g. times per year) and the expected service life for the floor covering (years) was selected.

Concerning the service life for floor coverings, it was decided to have it as a free parameter in the calculation program, motivated by the conclusions in Paper 3. It was suggested that the service life of the floor covering was more depending on the type of premise than the type of floor covering. In the scenarios, two different service lives were selected. For the type of premise where it can be expected that the change of floor covering follows the change of tenant, a service life of 8 years was selected for both types of floor coverings. As a value for another situation where economical or technical aspects can be expected to be the determining factors, a service life of 20 years was selected for both types of floor coverings.

The frequency of the frequent and periodical maintenance showed hard to generalise for the floor coverings professionally maintained in Sweden. For the scenarios, a frequent maintenance of 1,2 or 6 times per week was selected and a periodical maintenance of every $4^{th}$ year, every $2^{nd}$ year, or twice a year was selected. Totally 1296 scenarios have been analysed. In Figure 9 is shown an example of the input spread-sheet to the calculation program.

| Result | | |
|---|---|---|
| Service life | year | 20 |
| Floor area | $m^2$ | 1000 |
| Frequently maintenance | times at week | 3 |
| Periodical maintenance | times at year | 0,5 |
| Laundry machine | (yes=1, no=0) | 0 |
| Scrubber-drier machine | (yes=1, no=0) | 1 |
| Polishing machine | (yes=1, no=0) | 1 |
| Water temp. Wet-mopping | Degree °C | 25 |
| Water temp. scrubber-drier | Degree °C | 20 |

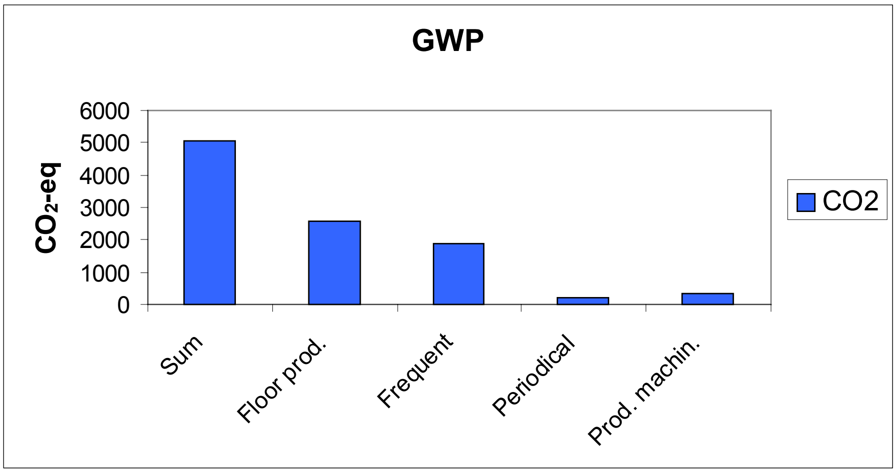
| **Frequent maintenance** | times at week | | 3 |
|---|---|---|---|
| **Scrubber-drier machine** | **Scrubber-drier** | | |
| | Allrent | (yes=1, no=0) | 0 |
| | Wax | (yes=1, no=0) | 1 |
| | Oil system | (yes=1, no=0) | 0 |
| **Recyclable mops** | **Moister mopping** | | |
| | Allrent | (yes=1, no=0) | 0 |
| | Wax | (yes=1, no=0) | 0 |
| | No cleaning agent | (yes=1, no=0) | 0 |
| | **Dry-mopping** | | |
| | Oil system | (yes=1, no=0) | 0 |
| | No cleaning agents | (yes=1, no=0) | 0 |
| | **Wet-mopping** | | |
| | Allrent | (yes=1, no=0) | 0 |
| | Wax | (yes=1, no=0) | 0 |
| | No cleaning agent | (yes=1, no=0) | 0 |
| **Disposable mops** | **Dry-mopping** | | |
| | No cleaning agent | (yes=1, no=0) | 0 |
| | Oil system | (yes=1, no=0) | 0 |

| **Periodical maintenance** | Times at year | | 0,5 |
|---|---|---|---|
| **PVC** | Untreated | (yes=1, no=0) | 0 |
| **PVC** | Polish | (yes=1, no=0) | 0 |
| | Wax | (yes=1, no=0) | 0 |
| **Linoleum** | Polish | (yes=1, no=0) | 0 |
| | Wax | (yes=1, no=0) | 1 |

**Figure 9. Input spread sheet to calculation program for floor covering (Paulsen 1999b).**

In the shown example in Figure 9 a 1000 $m^2$ linoleum covering with an expected service life of 20 years has been inventoried. It is maintained periodical every 2nd year with a Wax-system and the frequent maintenance is carried out using a scour-drier machine with a wax-system three times at week. The generation of hot water for the scour drier (20ºC) is included in this scenario.

The impacts from the cleaning agents have shown difficult to follow all the way to the endpoint. The final effects on the environment could not be estimated only with the knowledge of the types and amounts of emitted substances. As a category indicator for ecological toxicity, the amount of dry substances from the different agents has been used. For the resource use, primary energy has been used as a category indicator. Those two category indicators (dry substance and energy) have been used for the comparative analysis of the 1296 different scenarios. The calculation program, however, gives the opportunity to calculate the contribution to eight different effect categories with a specification of the contribution from the floor covering production, from the frequent maintenance, from the periodical maintenance and from the production of machinery to maintain the floor covering. In Figure 10 two examples of impacts on effect categories are shown, using the input from Figure 9.



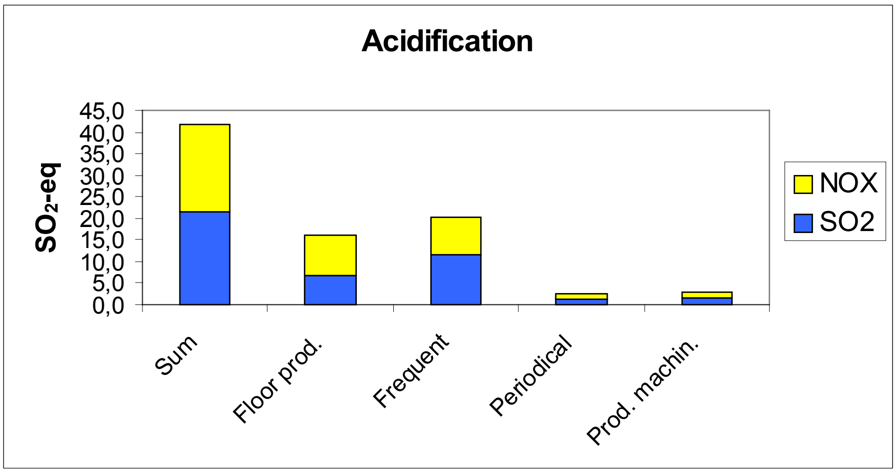




**Figure 10. Example of impacts on two effect categories from the calculation program (1999b).**

### 4.3.1 Conclusions from the inventory of maintenance of floor coverings

During the case study, an analysing tool was developed. With the help of this tool it is possible to take the maintenance into consideration when a choice of floor covering has to be done. The input parameters required are frequency of periodical and frequent cleaning, estimation of the service life and a choice between 36 different combinations of maintenance methods. The inventory of a huge amount of scenarios resulted in several interesting findings. One finding was that the usage phase in several cases showed to be very significant for the life cycle of the floor coverings. In some cases the impacts from the usage phase were even higher than from the production phase for the floor coverings. Further, it was shown that that the magnitude of impacts in the usage phase was related to the actual product choice and not only the chosen maintenance method. The difference in environmental impacts from the usage phase as a consequence of a product choice (e.g. linoleum in stead of PVC) showed to be a significant part of the product life cycle in several cases. In general it was found that the magnitude of environmental impacts from the periodical maintenance was depending on the choice of floor covering material. The frequent maintenance showed to be independent of the chosen floor covering material, but a significant contributor to the overall impacts and dependent on the type of periodical maintenance.

Another important outcomes of this inventory, are the methodological considerations, which have lead to a rough suggestion on how to handle the usage phase for building products in general (Chapter 6). A conclusion, specific for floor coverings, is that the results indicate that the best product or method chosen is not easily detected, seen from an environmental point of view, and depend largely on external parameters. The building specific data needed are here frequency of maintenance and cleaning and the kind of service life that is significant for the analysed type of premises. However, it is possible to elaborate with different scenarios to optimise the choice of floor covering together with an appropriate method for maintenance.

Also, an inventory of the different products and methods gives a picture of what is environmentally important, when choosing a floor covering. Hopefully, this will also be the case when other product groups are analysed.

# 5 Energy use in the usage phase, influenced by material choice (Paper 5)

During the studying of how the usage phase can be influenced by a building product, it was realised that the use of energy also could be influenced by the choice between different building products. It is obvious that a specific product choice can influence the energy consumption through the specific role and function of the product. Several product alternatives for the same application but with slightly different properties can cause a difference in the energy consumption. An important question is if this difference is significant in comparison to the other factors of the compared products life cycles. In Paper 5 it is argued that building products that are parts of the building envelope or that have a significant influence of the buildings thermal capacity, should be assessed for their influence on the energy consumption in a comparative assessment.

## 5.1 Scenario description for the energy study

The basic idea for a study was to connect an LCA-data base with supplying performance characteristics from building materials and an energy calculation program, to see how changes in material properties would influence the total energy use over the life cycle.

The calculation of energy use of a building can be done on different levels of accuracy and complexity. One desire was to find a simple approach, however, still taking heat storage into consideration. After several inventories of calculation principles and tools, it was decided to use the principles from the Dutch norm NEN 2916 (NNI, 1994), derived from the European EN 832 (EN 832, 1995). This method uses monthly averages for temperature and sun radiation and takes the effective heat capacity of the building into consideration, using a so called utilisation factor for the use of gained energy. The principles are explained in Paper 5. The Dutch norm NEN 2916 was transformed into a calculation program using material data to calculate the effective heat capacity and U-values for all building parts influencing the energy use. Then, a virtual 20-storey office building on 7000 $m^2$ was simulated, using the calculation program comprising the calculation principles from NEN 2916 and LCA-data for several building products. The office building was used to create three different scenarios to show that:

1) The significance of the role of the material in the energy consumption in the usage phase compared to its role on the production phase.
2) The need for an energy calculation model that takes the whole building context into account; gross errors can result from neglecting the context.
3) The importance of the effective thermal mass of the building, e.g. the availability of accessible high capacity elements for heat storage.

### *5.1.1 Scenario 1: Heat losses through external walls*

In scenario 1 five types of insulation materials was compared, all with slightly different in the thermal transmittance (U-value) and relative large variation in the LCI-profiles for the production phase, see Table 2.

*Table 2. Material data for some insulation products.*

| Product type | Designation | Trans. coefficient (W/m*K) | Embodied energy ($MJ/m^3$) |
|---|---|---|---|
| Fibre glass batt | R11 | 0,056 | 112 |
| Fibre glass batt | R13 | 0,045 | 186 |
| Fibre glass batt | R15 | 0,039 | 339 |
| Mineral wool | R16 | 0,036 | 450 |
| Expanded polystyrene | R17 | 0,033 | 2340 |

The comparison was done in three different geographical locations, which were Stockholm, Atlanta and Holland. The result showed clearly that the small changes in material performance regarding the U-value, gave a change in the energy use in the building which was much more significant than the change in embodied energy for the insulation materials, see Figure 11.

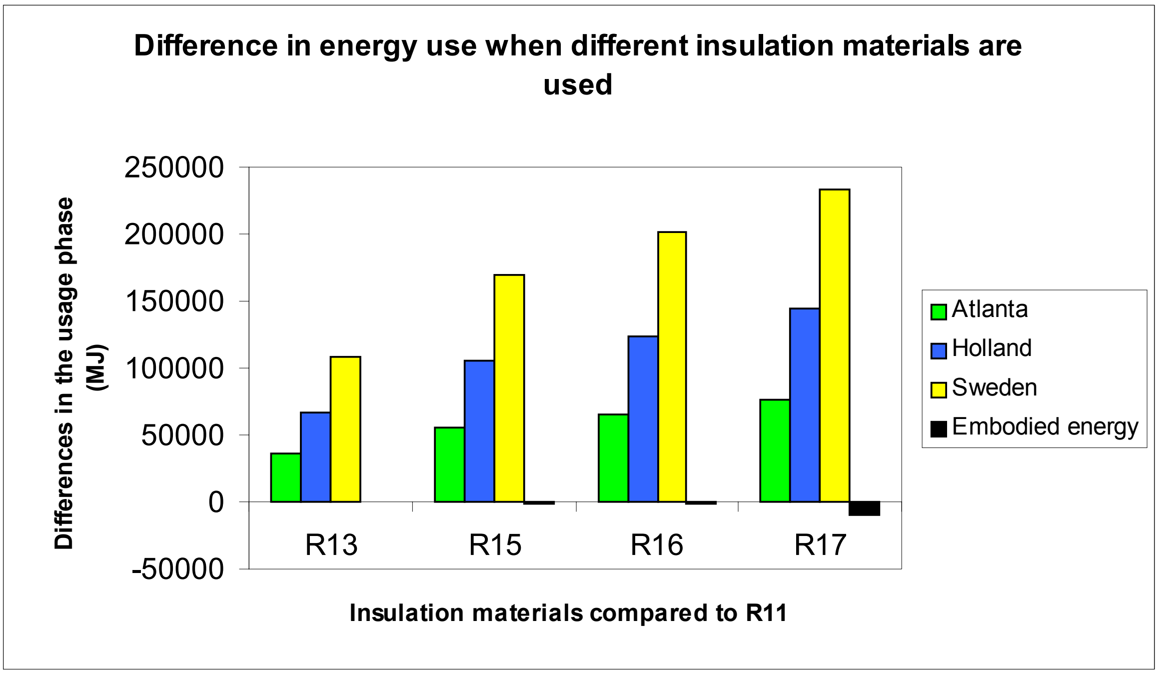



**Figure 11. Difference in energy use (saved energy) and embodied energy when changing the insulation material in the reference building. Values for three different geographical locations.**

### 5.1.2 Scenario 2: Influence of the building context

In scenario 2 the same five insulation materials was compared again (see Table 2), but only for Dutch conditions while a variation was done to the insulation properties of the windows in the building. In one case the U-value 1.2 W/m$^2$*K was chosen and in the other case, the U-value 3.0 W/m$^2$*K was chosen. This was done to see how the result was depending on the building context. A quite significant difference between the two cases was found, see Figure 12.

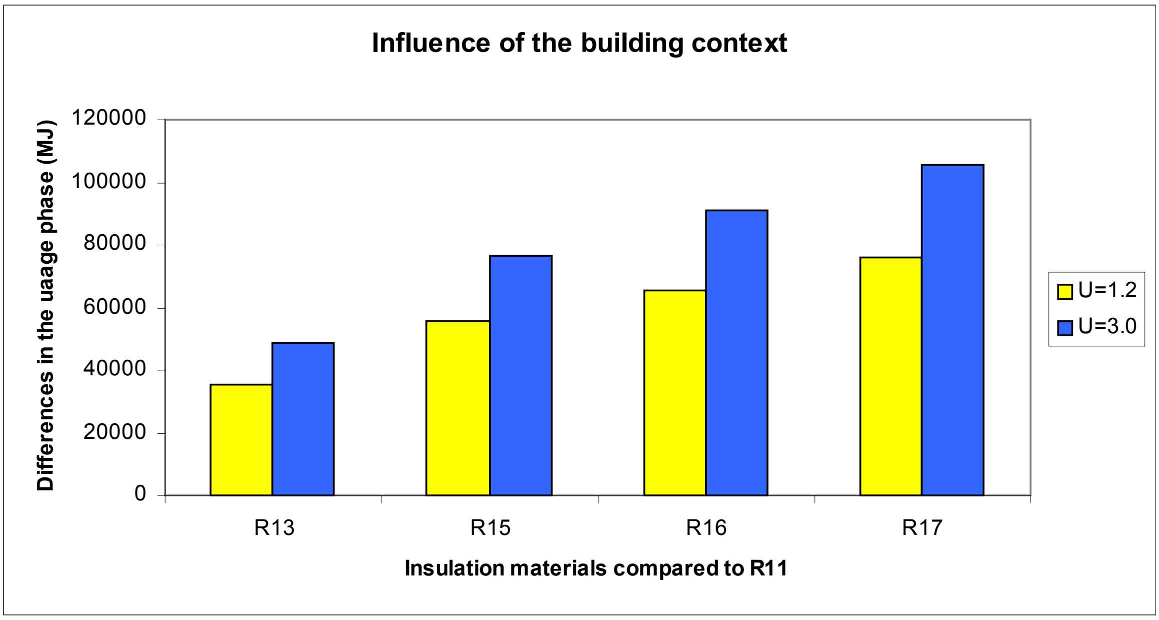



**Figure 12. Decrease in energy use using different insulation materials in the reference building. The magnitude is depending on the building context. Example with different U-value for the windows.**

However, if the different wall variants would have been studied separately (i.e. out of the building context), the actual differences between the two cases would have disappeared. The improvement of the insulation value of the walls in the initial case (U=3.0 W/m$^2$*K) returns more than in an improved case (U=1.2 W/m$^2$*K). It is thus obvious that context plays an important role to inform product choice decisions.

### 5.1.3 Scenario 3: Significance of the effective heat capacity

In the third scenario, the influence of the effective heat capacity was inventoried. Two different floor coverings was compared, both decreasing the access to the heat capacity of the underlying concrete floor and thereby decreasing the effective thermal capacity of the whole building. A PVC-flooring was compared to a carpet. The PVC- flooring reduced the effective thermal capacity of the concrete floor with 12 % and the carpet reduced the capacity with 56%. Further, the PVC had an embodied energy, which was twice the carpet. However the calculations showed that the difference in increased operation energy was much more significant than the differences in embodied energy, see Figure 13.

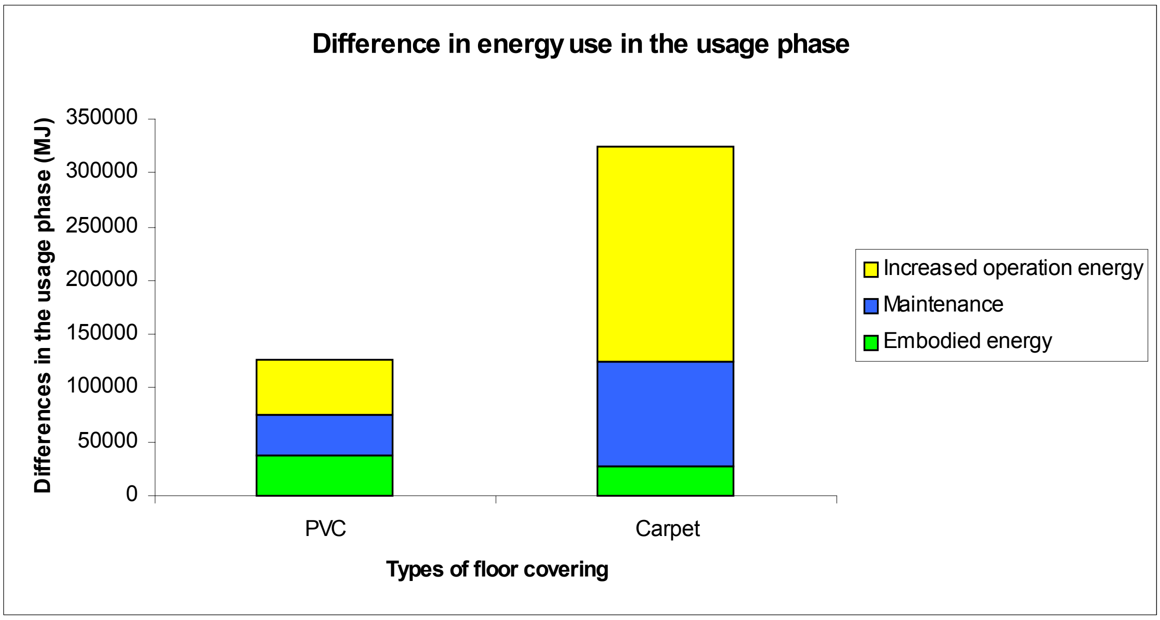



**Figure 13. Results from scenario 3. The increased energy use in the usage phase because of the reduced effective heat capacity of the concrete floor is compared with the embodied energy in the floor coverings and with the energy use for maintenance.**

## 5.2 Conclusions from the energy study

The energy study showed that even minor changes in some building material parameters could influence the energy use of a building during operation significantly compared to the embodied energy in the building materials. It is therefore suggested that the usage phase is always taken into account in an LCA-based material choice situation, in cases when the material influences the U-value of the building envelope or the effective heat capacity.

Further, it was found important to take the whole building context into account. To only consider a building part out of its building functional context, can lead to quite significant inaccuracies. As elucidated by the study, estimation methods not taking the whole building context into account can be too poor approximations and lead to wrong conclusions.

It is also important to notice that it was the difference in impacts which was inventoried when products were compared in a given application. Thereby, this “difference in impacts” can not be assigned the choice of a single product but only be regarded as a difference between two products in a given application.

# 6 Suggestion of a model for handling the usage phase for building products with the LCA methodology (Paper 6)

As mentioned in Chapter 3, it seems important to estimate the environmental impacts from the usage phase in several cases when performing an LCA for building products. Also, it is shown in Chapter 4 and 5 that the magnitude of the impacts from the usage phase, depending on building product choice, can be very significant for the whole life cycle. However, including the usage phase is not relevant for all types of building products and applications. In Paper 6 a procedure is suggested for how to proceed in a comparative building product LCA, and the main findings are reported here.

## 6.1 The proposed procedure

The procedure is illustrated in Figure 14 and shows a methodical way to analyse a building product with focus on the usage phase. It is based on two distinctive steps:

1) Identify if it is relevant to include the usage phase in a comparative assertion in the context of a building product choice. The relevant criterion is that the building products have a significant difference in environmental load in the usage phase regarding the current application (see Figure 6).
2) When it has been established that the usage phase is relevant and the types of loads are recognised, the viability to estimate their magnitudes has to be examined.

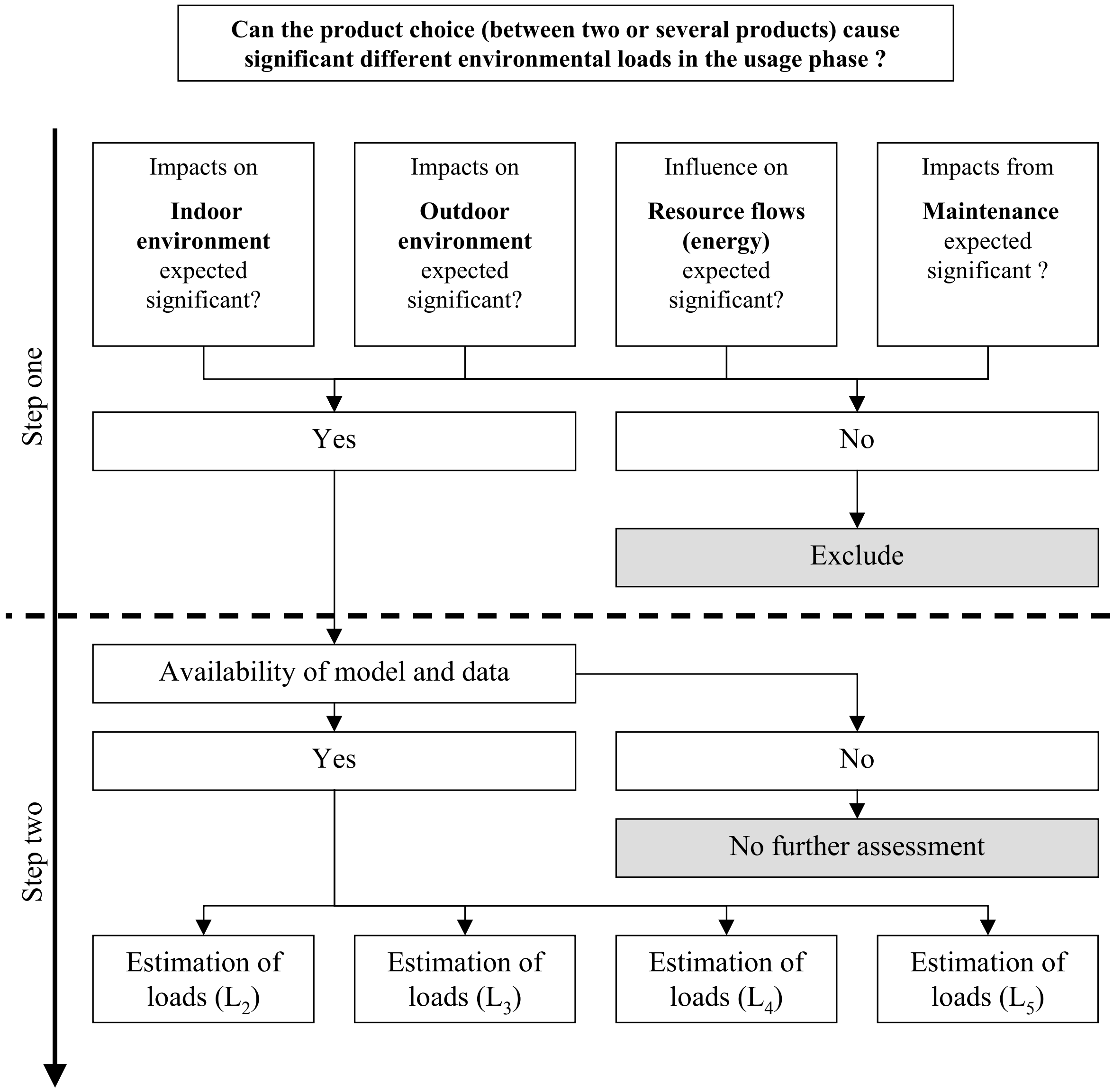



**Figure 14. Procedure to estimate environmental loads originating in the usage phase.**

## 6.2 Step one: Relevance of the usage phase

Four classes of sources of potential environmental impacts have been identified:

1) Emission to the indoor environment from products ($L_2$).
2) Emission to the outdoor environment from products, e.g. leaching of hazardous substances ($L_3$).
3) Interference with the resource flows in building systems, e.g. energy use ($L_4$).
4) Consumption of auxiliary products and resources for maintenance, e.g. cleaning or painting ($L_5$).

Emissions to indoor and outdoor environment and the impacts from maintenance do not need further explanation, however the conception “interference with the resource flows in building systems” is shortly explained in the following.

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 in the building sector. Water is not regarded as a particular polluting or scarce resource in Scandinavia and will not be further discussed. The relevance of including the usage phase depends on if any of the above mentioned four sources to environmental impacts are suspected to be of significance compared to the rest of the life cycle. Figure 15 illustrates the total loads over the product life cycle, calculated as “loads per year”. The loads ($L_2$-$L_5$) over the dotted line are impacts from the usage phase origin from four different sources. Actually, no exact answer can be given about the relevance of including the usage phase in this stage. The magnitude of loads and thereby their significance can only be determined after a full inventory of the usage phase. However, the problem with deciding what to include in an LCA is recognised in the ISO 14041 goal and scope definition (ISO 1998a) which states that: “Any decision to omit life cycle stages, processes or input/output shall be clearly stated and justified”. The first step of this procedure can then be seen as part of the justification of the inclusion or exclusion of the usage phase. If the outcome of step one is that the product choice will probably influence the environmental loads significantly, the actor can proceed to step two and assess the possibility to estimate the loads for the sources that have been identified.

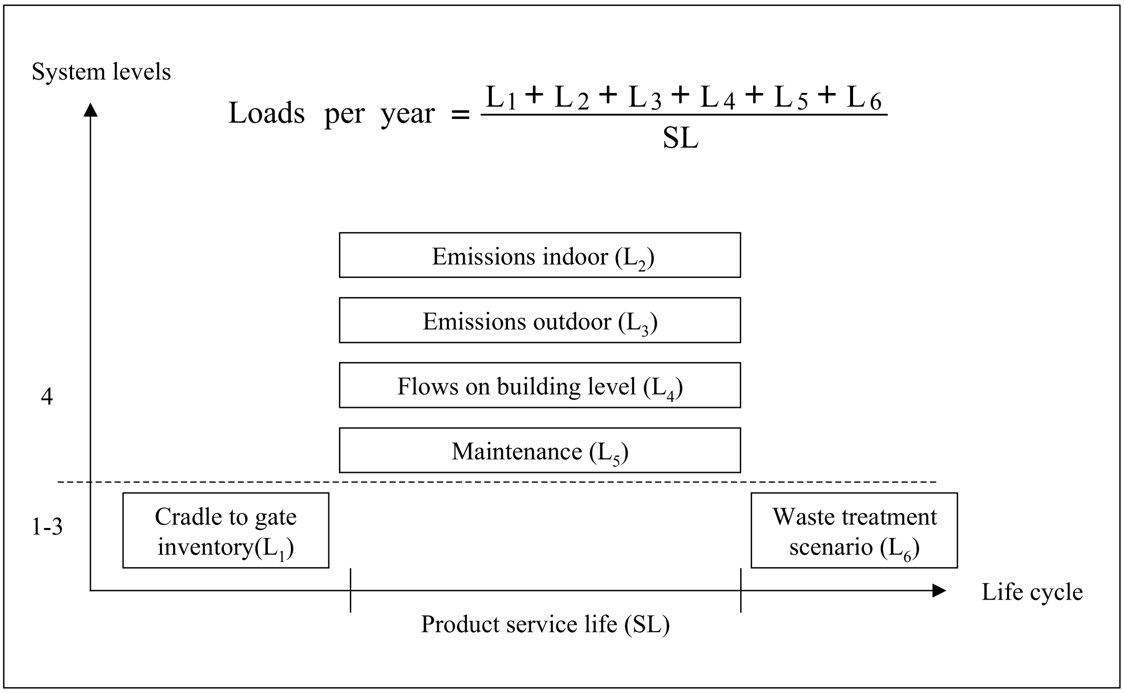



**Figure 15. Relevant environmental loads caused by a specific product choice, taking the whole life cycle into account.**

## 6.3 Step two: Assessing the possibilities to estimate the environmental impacts from the usage phase

As argued earlier, the choice of building product can influence the environmental impact from the usage phase even if those impacts cannot be predicted in a lower system level. In Figure 16 a principle is suggested for how to estimate the impacts for the product life cycle including the usage phase. First, a model is needed for how to estimate the impacts. Then, data from three different categories will be a need for:

1) LCI-data for the building products on the product level. This data is needed to estimate the impacts from the first and last stages of the life cycle. Further, other relevant product data can be needed to estimate the impacts from the usage phase. The data can be collected on system level 1-3 (see Figure 5).
2) LCI-data for the different types of impacts that can occur in the usage phase. For example, it can be LCI-data for different kind of resource flows like maintenance products or energy.
3) Building specific data for the actual application of the product. The building specific data can be parameters like "type of service life" and demands on maintenance. The data, which has to be collected here, depends on the data needed for estimating the magnitude of the expected impacts from the usage phase.

The data for 1) and 2) can be collected on system level 1-3 while the data for 3) have to be collected on system level 4 (see Figure 5). With a sufficient amount and quality of data it should be possible to give an estimate of the impacts in the usage phase, if it has been found relevant in step one of the suggested procedure.

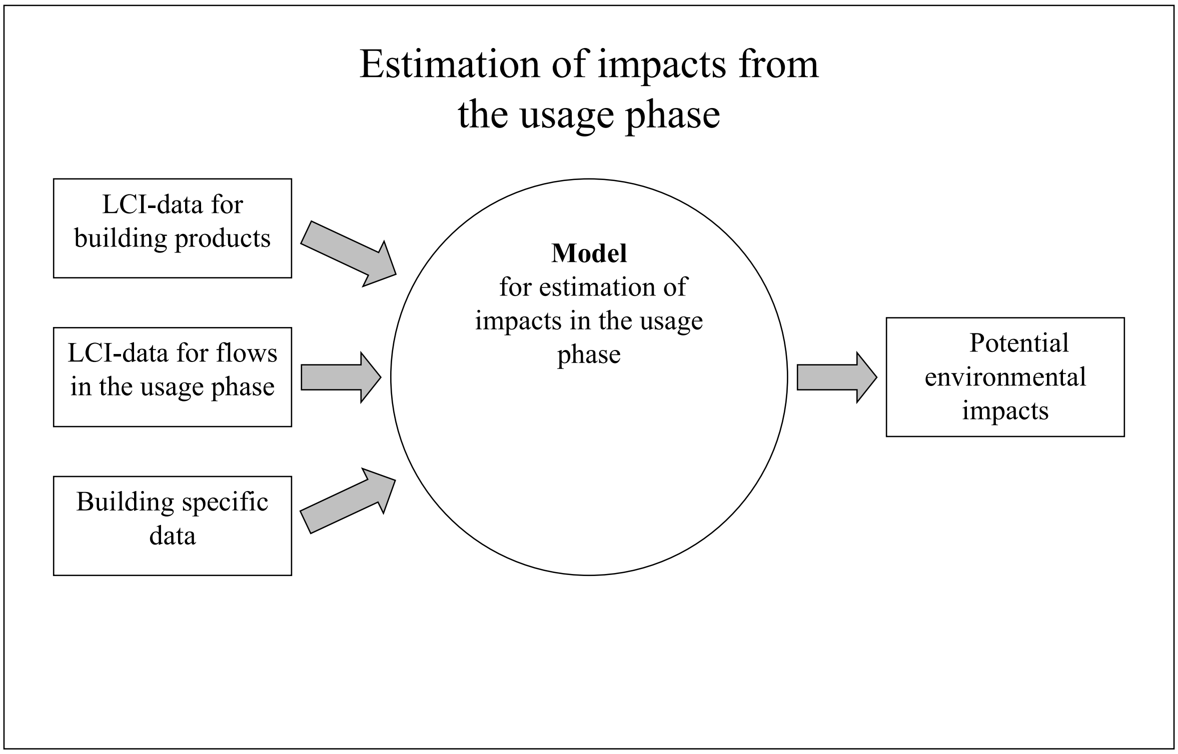



**Figure 16. Principle for estimating impacts for building products including the usage phase.**

## 6.4 Estimation of loads in the usage phase

Four different sources of environmental loads in the usage phase (caused by a specific product choice) have been identified. To estimate the magnitude of these environmental loads, several types of data are needed, but also models to handle the data in (see Figure 16). The present state of the art regarding models and data is discussed below.

### *6.4.1 Emissions to the indoor and outdoor environment ($L_2$ and $L_3$)*

The loads from indoor emissions ($L_2$) and outdoor emissions ($L_3$) have only been briefly handled in Paper 6 and the conclusions so far is that the principles from Figure 16 can be used for estimating the loads. However, more research is needed on this field where especially the models need to be developed. In contrast to the loads from maintenance and flows on building level, the "LCI-data for flow in the usage phase" (see Figure 16) origins from the building products.

### *6.4.2 Influence on resource flows on the building level ($L_4$)*

Flows on building level $L_4$ as energy use have been exemplified in Chapter 5 of this thesis. An office building was inventoried regarding energy use. The model was based an international standard for calculation of energy use for non-residential buildings. LCI-data for building products was used to compare the impacts from the whole life cycle for different material alternatives. Further, data regarding material performance was stored for the building materials together with the LCI-data. The impacts in the usage phase were related to the use of energy. Thereby, LCI-data for energy production of different alternatives was also included in the data collection to estimate the impacts from the flow in the usage phase. The building specific data was related to parameters for describing the office building as input to the energy calculation program. Also the choice of specific material alternatives could be seen as building specific data. The change in impacts as a consequence of different material choices could be compared to optimise the choice of material in an environmental point of view.

Comparing the study in Chapter 5 with the model suggested in Figure 16 regarding the possibility to estimate environmental impacts from the usage phase, it can be seen that data from the three types of data categories was used. The estimation of energy use was made possible using the principles from NEN 2916. In this standard, data for other types of non-residential buildings are given e.g. for health care buildings, sports buildings, etc. It should be quite simple to make scenarios with different material alternatives, even for these other buildings because the model and data exist. In principle, all types of building and material combinations should be possible to model with data on materials, energy systems, geographical data and building specific data. The fundamental idea is to connect the LCI-data and performance parameters from different material alternatives with an energy calculation program. It can be discussed if the principles of NEN 2916 are appropriate in all applications. However, the principles for estimating the impacts in the usage phase shown in Figure 16, can also be applied on other methods for estimation of energy use in the usage phase.

### 6.4.3 Impacts from maintenance ($L_5$)

Potential loads from maintenance $L_5$ have been analysed for floor coverings in Chapter 4. It was shown that maintenance in some cases could be significant for the product life cycle and also that the difference in impacts from maintenance could be significant between two product alternatives. An inventory tool was created to estimate the environmental impacts from the maintenance. To estimate the use of resources related to the maintenance, a model was needed for the maintenance performance. The model was possible to create because maintenance methods, products and equipment could be predicted and limited to a reasonable number. Further, it was reasonable to assume that the maintenance intervals were constant over time with the selected maintenance methods. LCI-data for the inventoried materials (floor coverings) was supplied to the model together with LCI-data for the maintenance products and equipment. However, to create scenarios, it was necessary to determine building specific data regarding maintenance intervals and expected service life. Actually, it can be concluded that the principles shown in Figure 16 were also applicable to this inventory. The significance of the usage phase, and possibility to estimate impacts from the usage phase for other product types, cannot be determined from the study in Chapter 4, which only regards two types of floor coverings maintained professionally. However, if the impacts from maintenance for another product type are suspected to have a significant influence on the product life cycle, some of the findings from the study on floor coverings can be used to determine the possibility to estimate the impacts from the usage phase. The first and most crucial topic is to determine if a maintenance scenario can be modelled. It can be asked if:

1) One can make a generalisation and limitation of relevant maintenance methods.
2) One can make a generalisation and limitation of relevant auxiliary products and machinery for maintenance.
3) One can assume that the intervals of maintenance are constant over time with the selected maintenance method.

Further it can be asked if LCI-data can be found for the auxiliary products and machines. Assuming that LCI-data exists for the actual product group (on product level) the final question to ask is if building specific factors like service life and frequency for maintenance can be estimated in the planning and construction stage depending on building product chosen.

Also it is here suggested that the maintenance is analysed using the definitions on maintenance in Table 3 as a control that all aspects of the maintenance are included.

*Table 3. Definition of intervals for different types of maintenance*

| Type of maintenance | Symbol | Frequency (example) |
|---|---|---|
| Frequent maintenance | F | Several times at month |
| Periodical maintenance | P | 0,2-2 times per year |
| Upgrading maintenance | U | Some time during the service life |

Finally it is suggested that the inventory is divided between auxiliary products used (e.g. paint, cleaning agents etc.) and the resource flow related to use of machinery (e.g. water and electricity).

# 7 Discussion

This whole thesis is aimed strongly on one topic namely the usage phase for building products. The structure of the building sector, as described in Chapter 3, with different system levels and many actors makes it very hard to predict how a building product will influence the environmental loads in the usage phase. The attempt in this thesis, to connect the material choice to their influence on the environmental loads in the usage phase, actually complicates the use of the LCA-methodology as a support tool because it has been recognised that the usage phase cannot be estimated regardless of the product application. The consequence is that building products, which significantly influence the environmental loads in the usage phase, have to be assessed in the construction phase. It would have been easier if the materials could be assessed regardless of their applications. The assessments could then have been carried out on material level.

The short building times and general time pressure under the planing phase do not favour the addition of environmental assessments of the consequences of different product choices. However, as mentioned in the introduction, it is important with a comprehensive view of the whole sphere, if an assessment of several products is carried out with the intention to improve the environmental profile. Actually this is the whole idea with using the LCA-methodology. It has been shown in this thesis that the influence on the usage phase (which often is omitted in a comparative building product inventory) in several cases can be very significant and thereby, should be inventoried to optimise a product choice. A methodological approach has been suggested, but there is still a lot of work to do on this topic. It can be asked how relevant the procedure in Chapter 6 is for the LCA-research in the building sector. I think that one finding, which is not stressed but nevertheless important, is related to the "step one" in the suggested procedure. The definition of the four sources to environmental loads makes it easier to justify an omission of the influence of the usage phase if the building product does not contribute to any of the four sources.

Regarding step two of the suggested procedure, the estimation of environmental loads in the usage phase is attempted to be done for maintenance and influences on operational energy. For the maintenance, an extensive inventory was carried out and a lot of work was done to compare two types of floor coverings. Roughly it can be said that the result of the inventory only regards the comparison of two floor coverings and besides, the assessment of chemicals is imperfect because of the lack of characterisation factors for the substances. However, I think that the findings and conclusions, which could be drawn from this inventory, can be seen as a framework with several empty spots to fill in. It is a lot easier to improve an existing framework like this than to start from the beginning. The methodological approaches, which have created during the inventory, can be tested for other types of building products, which need maintenance. Similar for the inventory of energy use presented in Chapter 5, it roughly can be said that the inventory only regards an office building with a few variations in materials and a lot of pre-defined values for the building. Further, the accuracy of the calculation can be questioned because the inventory has been restricted to monthly average temperatures in stead of dynamic simulations. Again it can be said that a framework has been created which of course can be improved in many ways. Using the same principles

(NEN 2916) several other types of buildings can easily be assessed using the same framework as presented in Chapter 5.

To make inventories of the usage phase for building products with no framework or data, is very time consuming. However, with a framework or tool in the planning and decision process it should be manageable to take the usage phase into account if it is regarded to be an important issue, because a specific material choice seems to be of special environmental importance. To make a tool applicable, like the ones developed in the inventories of floor covering and energy use for office buildings, it seems adequate to combine the environmental data with economical data. This would save analysis efforts and makes it possible to optimise the choice, with respect to both environmental and economical aspects. Another point of view is that a suggested method and products suggested in the model, cannot cover all possibilities. However, it is easier to analyse or develop a new product or method if a framework exists, which can be used for benchmarking. In that way, a framework or analysis tool together with relevant data can give feed back to all relevant actors involved in the impacts from the usage phase.

# 8 Conclusions and further research needs

## 8.1 Conclusions

One conclusion from the work performed during this thesis is that it seems very hard to perform a comparative LCA for building products when the range of information is limited to level 3 (meaning that the application and the condition for the products is unknown). However, the choice of material or product often has to be done in the planning or construction phase, where the knowledge on building level exists. The usage phase can then be regarded in a comparative analysis between building products to support a decision from an environmental point of view if:

1) LCI-data is available for the flows in the usage phase (like energy, maintenance products or product emissions).
2) LCI-data is available for the actual building products.
3) Building specific data is available (like expected service life and maintenance intervals).
4) A model for estimation of impacts in the usage phase exists.

If the usage phase is not considered when choosing building products, it could lead to sub optimisation. One way to generalise methods and auxiliary products is to co-operate with branch organisations when considering a specific type of product. Concerning the inventory of floor coverings, it was interesting to see that the optimal product choice (PVC or linoleum flooring) was depending on building specific factors like expected service life, frequencies for the different types of maintenance and type of cleaning method. Also regarding the inventory of energy use it was found that the consequences of a product choice was strongly depending on the building context and not only the product itself. This indicates that an optimisation of choice of building products (in an environmental point of view) only can be done with knowledge on system level 4, the building level.

## 8.2 Future research

As described in Chapter 6, the usage phase can lead to more environmental impacts than only from the maintenance and influence on the energy use of a building. Emissions to the indoor and outdoor environment are two other aspects to take into consideration. Of course, these two topics need further development, as does the maintenance topic and energy use topic.

Regarding the inventory of floor coverings, several areas with potential for improvement exist:

1) It is desirable to include several other types of floor coverings in the database as well as maintenance methods for the new floor types.
2) It would facilitate the interpretation of the inventory if the assessment of the chemicals could be developed.
3) A user-friendly interface for the analysing tool could be made and parameters like costs could be incorporated to make the tool usable for decision support in the building sector.

In parallel the inventory of energy use for office buildings could be improved in the same way

4) It is desirable to include several other types of buildings in the database as well as geographical data.
5) It would facilitate the interpretation of the inventory if the assessment of energy could be related to several scenarios for energy productions and related emissions.
6) A user-friendly interface for the analysing tool could be made and parameters like costs could be incorporated to make the tool usable for decision support in the building sector.

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