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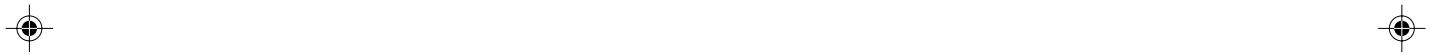
LUND UNIVERSITY

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



Recycling Potential and Design for Disassembly in Buildings

Catarina Thormark





Recycling Potential and Design for Disassembly in Buildings

Keywords

Buildings, Building Products, Building Waste, Recycling Potential, Recycling, Design, Disassembly, Deconstruction, Environmental Assessment, LCA

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Lund University, Lund Institute of Technology,
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ISRN LUTADL/TABK--1021--SE

Lund University, Lund Institute of Technology
Division of Building Science
P.O. Box 118
SE-221 00 LUND
Sweden

Telephone: +46 46 222 73 52
Telefax: +46 46 222 47 19
E-mail: bkl@bkl.lth.se
Homepage: <http://www.bkl.lth.se>



Abstract

Recycling as part of environmental considerations has become a common feature in architecture and building construction. Recycling of building waste can make a considerable contribution to reducing the total environmental impact of the building sector. To increase the scope for recycling in the future, aspects of recycling have to be included in the design phase. Design for disassembly is a key task to increase the future scope for recycling.

One object has been to elucidate the environmental effects due to recycling of building waste. The research has been limited to recycling of building materials, its possibilities and its environmental effects. It does not include a reuse of the building itself. Nor are effects on the indoor climate, on economy or on the working environment included.

Another object has been to find a method for assessing the recycling potential in buildings and for comparing the recycling potential of buildings with reference to the initial construction. The recycling potential can be briefly described as a way to express how much of the embodied energy and natural resources could, through recycling, be made useable after recycling.

It has also been an object to formulate guidelines for a design for disassembly.

The research work has been mainly performed through theoretical studies, collecting experiences from practitioners and through case studies. In case studies established methods of life cycle assessment and the, in the thesis suggested, recycling potential approach have been used. Constructions and recycling scenarios were varied.

A brief overview of how recycling is handled in different assessment methods is presented. A method for assessing the recycling potential is suggested. The recycling potential has been calculated for different buildings and the annually produced building waste in Sweden. General guidelines are given for design for disassembly in building construction. Measures and future work are suggested to increase recycling.



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Terms

Allocation. The process of assigning material and energy flows as well as associated environmental discharges of a system to the different functions of that system.

Calorific value. The amount of heat released by a unit weight or unit volume of a substance during complete combustion.

Combustion, as form of recycling. Combustion with energy recovery.

Embodied energy. The sum of the energy used to manufacture a product from cradle up to the product is ready to be delivered from the producer and of its feedstock.

Emission. Release or discharge of any substances, effluents or pollutants into the environment.

End use energy (Final energy use, bought energy). The energy consumption measured at the final use level. For a building, energy inflow measured at the gate of the building, excluding passive solar gains and heat recovery from human beings.
Antonym: primary energy use.

Environmental impact. A change to the environment, whether adverse or beneficial, and the associated consequences for both humans and other ecosystem components caused directly by the activities of product or service development and production, wholly or partially resulting from an organisation's activities, products, or services, or from human activities in general.

Feedstock. The heat of combustion of raw material inputs - not used as an energy source - to a product system.

Heat of combustion is expressed in terms of higher heating value or lower heating value. Feedstock energy quantifies the potential of a material, such as wood or plastic materials, to deliver energy if it is burned with heat recovery after its use life as building material.



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Hazardous waste. Waste requiring special disposal techniques. Different countries have different definitions and regulations, and national standards are frequently changed.

Heating value. Heating Value is defined as the amount of energy released when a fuel is burned completely and the products are returned to the state of the reactants. The heating value is dependent on the phase of water/steam in the combustion products. If H_2O is in liquid form, heating value is called HHV (higher Heating Value). When H_2O is in vapour form, heating value is called LHV (Lower Heating Value).

Impact category. A group or class of inventory inputs and outputs that shares common environmental attributes such as a mutual mechanism of action that can lead to a possible endpoint.

Life cycle. Consecutive and interlinked stages of a product system, from raw material acquisition or generation of natural resources to the final disposal.

Material recycling. Recycling where the material is used as raw material for new products. Material recycling can be in open or closed loops, i.e. the material is used as raw material in a new product of different respectively of the same kind as the original product.

Net energy. The Embodied energy less the Recycling potential.

Precombustion energy. The total energy used to produce, transport and store a fuel during its whole life cycle upstream its use by burning.

Primary energy. The energy consumption measured at the natural resource level. For electricity, the primary energy used to produce 1 kWh is a mix of several primary energies: fossil fuels (crude oil, natural gas, uranium), renewable fuels (biofuels, wood) and energies (hydropower, solar, wind, tidal). This mix is a characteristic of a country and may vary significantly.

The conversion from final use of electricity to primary use needs thus assumptions about the structure of the electricity production and about the conversion efficiency of electrical power plants.

Recycling. Recycling is used as a generic term for different forms of recycling. The here included forms are; reuse, material recycling and combustion with heat recovery.



Terms

Recycling potential. The environmental impact from production of that material the recycled material will be a substitute for less the environmental impact from the recycling processes and connected transport.

In this thesis the environmental impact is limited to embodied energy and use of resources. The recycling potential can therefore shortly be described as a way to express how much of the embodied energy and natural resources which, through recycling could be conserved.

Reuse. The material is used for about the same purpose as initially. Re-use might imply upgrading or some renovation.

Service lifetime.

Sustainable development, sustainability. Meeting the needs of the present without compromising the ability of future generations to meet their own needs; combining economic growth and greater prosperity with environmental and social quality for people around the world.

There are a very large number of suggested definitions on sustainable.

Weighting. Weighting is an optional procedure to rank, or possibly aggregate, the results across categories. Weighting is based on value choices. The combination of categories is not typically based on scientific knowledge.



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Preface

This report will, together with my licentiate thesis, make up my doctoral thesis.

The background to the research project are the environmental problems within the building sector connected with the use of natural resources, energy and the production of waste. There are three main problems. (i) The supply of certain natural resources, for example gravel, is diminishing. (ii) The production of building materials requires a considerable amount of energy. (iii) The space for landfills is difficult to provide in densely developed areas and landfills can cause leaching of harmful substances.

When I started my research in 1994, recycling was attracting general attention in society and was assumed to be an important means of alleviating the problems described above and achieving a sustainable society. Based on this assumption, the initial aim of my research was to “develop guidelines pertaining to the aspects of recycling for use by the actors in the design process”.

However, the aim of most research projects tends to change, and so did the aim of mine.

My research came to circle around three basic questions; (1) Is recycling of building materials worth while? (2) If recycling of building materials is worth while, how can aspects of recycling be included in the design stage? and (3) How can the benefits from future recycling be assessed and included in the assessment of buildings?

This report will present the results of my circling. Hopefully it will also provide a platform for a discussion on the issue and for further research.

Harlösa, February 2001
Catarina Thormark



Recycling Potential and Design for Disassembly in Buildings





1 How to read this report

This report will give an introduction to the field of recycling building materials and present my main results and conclusions. It is also intended to provide a platform for a discussion on the issue of recycling building waste and on further research within the subject.

The headings will hopefully guide the reader to the information he or she is looking for. However, a short complement to the headings will be given below.

The way the different chapters build up the structure of this report is illustrated in Figure 1.1. To a certain extent, when the many excluded loops and dead ends are disregarded, the figure also illustrates how the work proceeded.

Chapter 2

Today both environmental aspects and recycling are handled with evidence (this does not sound right. What do you mean? confidence?) within the building sector. Different processes have together played important parts in this development. This chapter will give a short historical review of these processes and of the handling of building waste. It will also describe the initial questions in this thesis and how the focus of the thesis changed.

Chapter 3

This chapter will present the aim, method and limits of the thesis. The basic concepts used in the report will also be presented.

Chapter 4

In this chapter, the main benefits of recycling as well as different aspects of recycling will be presented. The chapter will start with a brief analysis of the supply of the most important resources used for building materials.



Chapter 5

This chapter will present some different tools and assessment methods for either choosing building materials or for assessing the whole building with respect to the environment. The tools and methods will be briefly described with the focus on how they handle aspects of recycling.

Chapter 6

This chapter will present the theoretical principles of the recycling potential concept. Important parameters that have to be included will be discussed as well as some basic difficulties and weaknesses with the approach. The difficulties in predicting the future will also be discussed.

Chapter 7

In this chapter, some general guidelines will be formulated for use in the design process of buildings, i.e. for architects and engineers. The guidelines are based on knowledge gained during the work and on results from the case studies. The chapter will start with a few words about design for disassembly in product design.

Chapter 8

In this chapter, three issues will be touch upon; the significance of the used methods for the results, the significance of the chosen case studies for the results and *recycling materials* versus *reuse of the building itself*

The content of Chapter 9, Conclusions, and Chapter 10, Further research, will need no explanation.

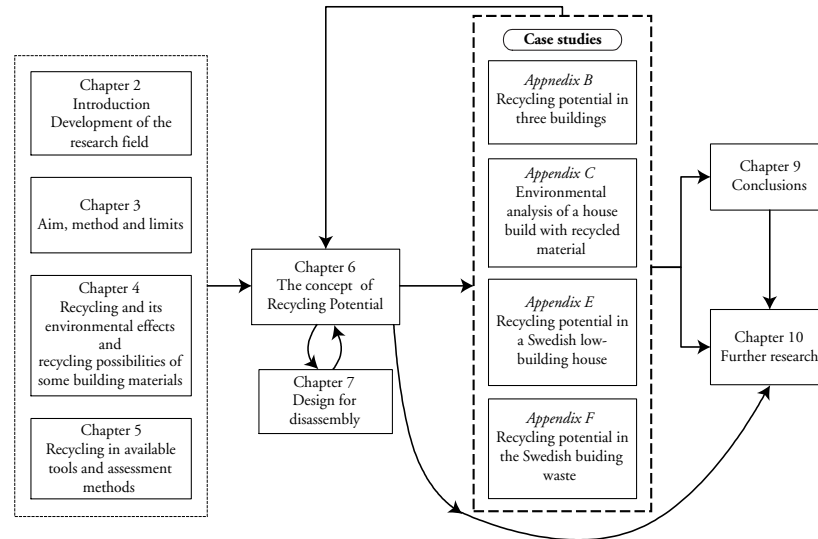


Figure 1.1 The figure illustrates how the different chapters build up the structure of this report. To a certain extent, when the many excluded loops and dead ends are disregarded, the figure also illustrates how the work proceeded.



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2 Introduction

Today both environmental aspects and recycling have become evident issues within the building sector. Different processes have together played important parts in this development. This chapter will give a short historical review of these processes and of the handling of building waste. It will also describe the initial questions in this thesis and how the focus of the thesis changed.

2.1 Background

In the 1970s and 80s, the environmental concern in society focused on the production processes. Environmental regulations concentrated on the pollution from industries. However, at the end of the 1980s and during the 90s, it was increasingly recognised that both the use phase and the disposal phase of the product life cycle can be very important. This requires a new approach to product design, one which results in a product designed for all the stages of its life cycle.

Sustainable development is today a world-wide key issue for individuals as well as business, industries and governments. For the building sector this means that buildings must be produced with a minimum of environmental impact over their whole life cycle. The focus has mainly been on minimising the energy for operation and optimising the use of building materials. A sustainable development also requires the consideration of conversion of resources and energy by applying a closed system approach. This means recycling, the use of recycled materials and a design that facilitates recycling.



2.2 The research subject and how it developed

This thesis can be regarded as coming within the field of design for disassembly which in turn can be regarded as part of 'sustainable building'. Design for disassembly is a design aiming at a construction which is as easy as possible to dismantle, i.e. a design which facilitates future reuse or recycling of included materials or components. It is a new field of research with roots in several processes. A brief outline of different processes which together have led to and contributed to the development of both recycling and design for disassembly in building design is given below.

Agenda 21

An important process is here symbolised by Agenda 21 (Agenda 21, 1993). The document Agenda 21 was a result of the Rio Conference in the year 1992. The agenda was followed by documents on national level. The Swedish document was the Ecocycle Bill, written in 1993 (Ecocycle Bill, 1993). The bill was a proposal from the government and accepted by the Swedish parliament, with the aim and vision of a society based on an eco-cyclic approach. In the bill it was stated that a root cause of the environmental disorder is the prevailing tradition of 'linear production process'. This process starts with extraction of natural resources and ends with products in landfill. In the bill both prevention of environmental impacts and recycling are pointed out as important means of decreasing the environmental disorder.

As far as the building sector was concerned, a specific result of the bill was the establishment of the Ecocycle Council for the Building Sector (Byggsektorns kretsloppsråd). It was established by the players in the building sector in order to reduce the environmental impacts of the building sector. One of its aims was to halve the amount of building waste to landfill (Byggsektorns kretsloppsråd, 1995).

Energy use in a life cycle perspective

Another process which has actually resulted in increased attention to the potential of recycling is the research of energy use in buildings. This research has a long tradition and started with a focus on the energy requirement for heating since heating accounts for the dominant part of the total energy needed for operation. The more the energy needed for heating was reduced, the more interesting became the other requirements for



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energy, for example the energy needed for household electricity. In the last years, the perspective has been extended to a life cycle perspective and the energy needed for production of materials has been included. In the beginning of the use of this perspective, the demolition of a building was often regarded as the end of the life cycle. The life cycle perspective was the perspective of the building itself. Later, however, the research also started to pay attention to the possibilities of recycling.

Building waste as a cost problem

Parallel to the above processes, there was a process which to a great extent emanated from the *costs* associated with the building waste. In Sweden this process mainly started in the 1970s. It was observed that building waste gave rise to high costs in both building and demolition. The waste, transport and treatment were often invoiced per m³. A common measurement of waste handling and its costs was the degree to which the waste containers were filled. The containers were judged to contain about 80% air as a great part of the waste consisted of wood (Hägglöv, 1978). The building sites which were considered to have a rational handling of the waste filled the containers to about 60%.

On the building site, spill generated costs for two reasons; purchase of new materials and payment for waste handling. For specific materials, the spill accounted for as much as 25-30% of the total amount of purchased material (Larsson, 1983).

Result of the above processes

The processes very briefly described above have together played an important part in the development of a new approach within the building sector. Both recycling and environmental aspects are today regarded as natural issues to include in the building process. See figure 2.1.

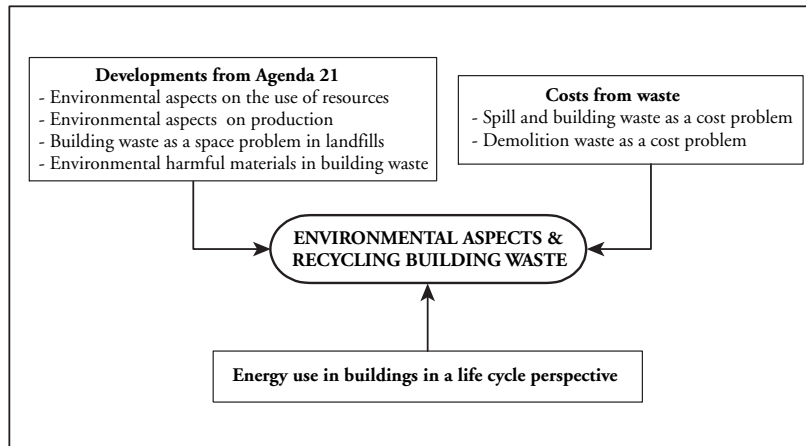


Figure 2.1 *Different processes which have played an important part in the increasing interest in recycling building materials and in the environmental aspects.*

When the above processes are combined, the obvious questions to ask are how to recycle, how to use recycled materials and how to design new products in order to facilitate recycling at the end of the life of the building.

Recycling is pointed out as a means to decrease the use of natural resources, decrease the use of energy and decrease the need of land area for resource extraction and landfill.

Design for the environment (in the literature known as ecological design, green design, environmental conscious design, sustainable design, design for recycling, design for disassembly etc) became a new research field in product design. Systems were developed for disassembly, recycling techniques, design methods etc for computers, cars, vacuum cleaners, weapons and all kinds of products. In the very recent years, the question of design for disassembly and recycling has also been raised within the building sector.



2.3 Recycling in the Swedish building sector

As late as in the 1970s, building waste was in general handled in four ways (Eriksson, 1974).

- burning combustible waste in open fires on the building site (unless the smoke was expected to be disturbing)
- burying the waste on the building site
- transport to landfill
- transport to other building sites

In a study from 1974, the problems connected with *building* waste were concluded to be very small compared with other waste categories. The economic scope for recycling was also considered to be very small (IVA, 1974).

About one third of the waste was assessed to consist of wood and paper. In the late 1970s after the “energy crisis”, the question of the cost of waste was combined with the question of wastefulness. To put wood and paper waste to landfill was by some people regarded as wastefulness. Studies were started to find options for recovery of wood, paper and metals (Hägglov, 1978).

Later however, the cost aspect was complemented by environmental aspects. Apart from being a cost problem, the building waste was also shown to be a landfill problem. The *space* for landfill, especially in densely populated regions and the *environmental impacts* from landfills in terms of leakage, became increasing problems. Further, attention was also paid to the environmentally harmful parts of the building waste (Sigfrid, 1993). Examples of these are mercury, cadmium, asbestos, lead etc.

A great number of activities regarding both cost reduction, waste reduction and later on recycling were carried out in Sweden during the 1980s and 1990s. Examples are analysis of the amount and the composition of building waste (Sigfrid 1993, 1994a, SNV, 1996), amount of spill (Warte, 1981, Larsson, 1983, SBUF, 1990, Linde, 1996), reduction of spill by pre-cutting (Westman, 1993), scope for recycling (Brismar, 1982, Larsson, 1987, Sahlin, 1991, Sigfrid, 1994b, numerous publications from the Swedish National Board of Housing, Building and Planning) and sorting at the building sites and scope for reuse of packaging etc. (Asplund, 1994, Sahlin, 1994).



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It was observed that the decisive conditions for recycling were the sorting of waste and the market for recycled materials. It was concluded that the most effective sorting was achieved by sorting at the building site or demolition site. Studies of selective demolition began, for example (Johnsson, 1995, Persson, 1995, 1996, Sternudd, 1997). The studies were greatly inspired by activities in Denmark.

In actual fact, the discussion on recycling building waste did not really start in Sweden on a large scale until the beginning of the 1990s when increased attention was paid to the environmental aspects. The interest was much inspired by activities abroad and a lot of knowledge and experiences were collected from, for example, Denmark, Holland and Germany. The motives for recycling, however, varied in different countries but the dominating Swedish motive was the environmental aspects.

There are no really reliable figures on either the amount of building waste or on the recycling rate. A lot of figures have been presented but mostly without references. The figures are mostly based on assessments of rough estimations. When these figures are compared the lack of reliability is obvious. The results from two Swedish investigations, reported in (Byggsektorns., 1997), gave 1,9 and 5 millions of tons respectively. The main reason for this is the lack of statistics on demolition, waste production and waste treatment. The situation is to a great extent also valid for other countries. Besides, there is no clear definition of what is to be included in 'building waste' or how 'recycling' is to be defined. This explains the astonishing differences between reported figures from different countries, regarding both the amount of building waste and the amount recycled. For example, in a survey from 1996 of the annually produced building waste in European countries, 140 kg/capita was reported for Sweden while 6 750 kg/capita was reported for Luxembourg (Lauritzen, 1996).

In the year 1990, it was estimated that about 91% of the Swedish building waste was put to landfill. About 5% was burnt and about 4% was recycled (Byggsektorns., 1997). In 1996, it was estimated that about 60% was put to landfill, 12% was burnt and about 19% was recycled (SNV, 1996). However, in view of the uncertainty in the statistical background, these figures should be viewed with caution.

Regarding the market for recycled materials, important problems and constraints were identified, for example how to define and test the quality of recycled materials, how to organise temporary storage of recycled materials and how to find materials available for reuse etc.

In the very last years of this discussion, the question has been also raised of how to include recycling aspects in the design phase of new buildings in order to facilitate future recycling.



2.4 Design for disassembly and recycling in building design

Design for the environment (sustainable design etc) is well established in the field of research into building design. During the very last years, several conferences have been held on these themes.

Recycling of building materials as well as deconstruction is a new subject which has attracted increasing interest. Recycling of building materials and deconstruction of buildings are increasing both in Europe and USA. At CIB, International Council for Research and Innovation in Building and Construction, the task group 39 was formed in 1999. The goal of TG39 is to produce a comprehensive analysis of, and a report on, worldwide building deconstruction and materials reuse programmes that address the key technical, economic and policy issues needed to make deconstruction and reuse of building materials a viable option to demolition and landfill. The hoped outcomes are an acceleration in the pace of component reuse in building construction and a shift to Design for Disassembly.

The question of design for recycling or design for disassembly is often raised and pointed out as a new field to focus on. In the very last years, some research projects have started on this issue.

The aim of these projects is to develop an analytical framework which enables a circular systems methodology to be applied to the built environment

2.5 The initial question and how the focus changed

The initial object of this research was to develop guidelines pertaining to the aspects of recycling. The guidelines were to be addressed to the actors in the design process in order to facilitate recycling of building materials in a future reconstruction or demolition. It was decided to study generally used building techniques. It seemed to be a question of choice of materials, avoidance of materials that would complicate recycling or even make recycling impossible and finally, use of joints suitable for disassembly.

As a start, it seemed important to identify the materials and the elements of construction in a building which would be most important to improve regarding the potential for recycling. This knowledge would then



Recycling Potential and Design for Disassembly in Buildings

be complemented with knowledge about materials which disturb the recycling process, and knowledge about joints suitable for disassembly. The intention was then to perform case studies. It was assumed that it would be possible to formulate tangible guidelines on the basis of the results from the case studies.

However, when the project had proceeded for a while, some things became clearer. To identify the materials which disturb recycling, knowledge and experiences from the producers and the recyclers had to be put together. When this project started in 1993, the knowledge and the experience of the producers and the recyclers of building materials was found to be all too small to carry on the project in this direction. Further, the design of joints suitable for disassembly appeared to be a problem most appropriately solved by the material producers. Besides, there was no obvious method for assessing the benefits from and the potential for recycling. It also became evident that such a method had to include a large number of different parameters and, in turn, it was not clear how these could be 'measured'.

For these reasons the work came to change and instead focus on the following questions.

- How to express, measure and compare the recycling potential?
- Is recycling of building materials worth while? What are the environmental effects from recycling in terms of energy, natural resources and waste to landfill?
- Which parts of a building have a high energy use in production but small recycling potential, that is, are most important to adapt to recycling? (Environmental impact is here mainly limited to use of energy and resources.)
- How does the recycling potential differ between different types of constructions?
- To what extent does the form of recycling affect the recycling potential of the constructions?
- What are the main obstacles to recycling in different types of constructions?

The main object of the project also changed, from aiming at tangible proposals to more general proposals.

It is hoped that the result of the work will contribute to, or provide a basis for,

- research on how to define the recycling value
- reference values on the recycling potential of buildings



Introduction

- politicians and authorities to initiate demands for the recyclability of buildings
- contractors to include recycling aspects in building programmes
- architects and engineers in choosing materials and constructions
- producers of building materials in developing constructions for disassembly
- developing tools for the assessment of buildings, tools that will include the recycling potential.



Recycling Potential and Design for Disassembly in Buildings





3 Aim, methods and limits

This chapter will present the aim, method and limits of the thesis. The basic concepts used in the report will also be presented.

3.1 The Aim of the Thesis

The aim of this thesis is to

- provide an outline for a model to express, measure and compare the recycling potential of buildings or building elements
- determine environmental effects due to recycling of building waste in terms of energy, natural resources and waste to landfill
- analyse how the recycling potential varies between different types of constructions
- analyse to what extent the form of recycling affects the recycling potential of different constructions
- identify which parts of a building have a great impact on production but a small recycling potential
- identify some main obstacles to recycling in different types of constructions
- provide general guidelines pertaining to the aspects of recycling for use by the actors in the design process in order to facilitate recycling of building materials in a future reconstruction or demolition

3.2 Method

Introduction

The research work has been mainly carried out through theoretical studies, collecting experiences from people in practical work and case studies. The field of research is new and the work therefore necessitated a lot of



Recycling Potential and Design for Disassembly in Buildings

work to find a suitable method. The subject includes aspects from numerous fields. Knowledge and experiences from several different fields had to be collected and combined.

In case studies the embodied energy of buildings was calculated and compared with the recycling potential in different recycling scenarios. The recycling potential can be briefly described as a way to express how much of the embodied energy and natural resources could through recycling be made useable after recycling. The concepts embodied energy and recycling potential are defined later in this chapter.

As the field is new, there was very little literature focusing on the subject. Useful knowledge could however be collected from the literature on cleaner production, design for disassembly in product design, environmental assessment of buildings, building science, material science, service life assessment, life cycle assessment, energy production, incineration techniques etc.

The suggested concept 'recycling potential' was to a great extent a result of my reflections on applying available allocation methods within life cycle assessment to buildings.

Information on disassembly techniques, recycling techniques and the scope for sorting were only available through interviews. In the very last years, however, some documentation of case studies of these aspects has become available.

Embodied energy of a building

Embodied energy is a well established concept for all energy required for the processes from the extraction of primary resources up to the time the product is ready to be delivered from the producer. The calorific value of the materials is included.

For the calculation of the embodied energy of a whole building, the system boundaries in *space* (building elements to be included) and *time* (phases in the production and the life time of the building) have to be defined. The calculation includes specification of included materials and their quantity, data on the embodied energy of these materials and transport distances from the supplier to the building site, as well as the means of transport.

Data on embodied energy for building materials can be collected from the literature. The data can be site specific, i.e. data from a specific producer, or branch specific, i.e. average value from several producers.

Data can vary considerably between different references. In general, newer data is more transparent than older data. The reported energy use is sometimes lower in newer references than in older references due to greater efficiency in the industrial processes. Sometimes, however, newer



references report a higher energy use because more processes have been included in the study. Differences can also be due to the allocation methods used and whether electricity is presented as bought electricity or primary energy.

It can often be very difficult to assess the differences. Comparisons of the embodied energy/m² living area of a building should therefore be regarded with caution. However, the data quality is of minor significance for the recycling potential as it is expressed as a proportion of the total embodied energy.

It is obvious that the more detailed is the calculation of a building, the more precise is the result, and the question of what to include in an assessment is one of time versus precision. Parts of minor significance can be excluded without influencing the total result. However, it can be difficult to judge what parts are to be considered as of minor significance. This can be illustrated by an example. The energy for transport to the building site was in a specific case about 5% of the total energy use. Transport can then be said to be of minor significance. If the same building was instead built with reused materials from a distance of 250 km and with energy extensive material, the total energy use would have been about halved. The energy for transport would in this case account for about 20% of the total energy use.

A building's total energy use during its life time, E_{tot} , is generally calculated as

$$E_{tot} = E_{material} + E_{transport\ to\ site} + E_{erection} + E_{renovation} + E_{operation} + E_{demolition} \quad (3.1)$$

where

E_{tot}	is a building's total energy use during its lifetime
$E_{material}$	is the embodied energy of included materials
$E_{transport\ to\ site}$	is the energy need for transports of all building materials to the building site
$E_{erection}$	is the energy need on the building site
$E_{renovation}$	is the embodied energy of substitute materials
$E_{operation}$	is the energy need for heating, ventilation, electricity for pumps and fans and household electricity
$E_{demolition}$	is the energy need for demolition/deconstruction of the building



Energy use as an indicator of environmental impact

The effects of recycling which are dealt with in this thesis are mainly limited to the use of energy. To some extent the use of resources and the amount of waste produced which is driven to landfill are also included.

Energy has been used as an environmental indicator mainly due to lack of data. When this work started, life cycle data on building materials mostly included only energy use. Most often the data were aggregated and a breakdown by different fuels was not presented. Data on the use of raw materials and on emissions only existed for very few materials. Because of this, inclusion of emissions etc was not possible at all.

It is only in very recent years that life cycle data, with information on use of resources, use of energy and emissions to air, water and soil have been produced for a large number of building materials. Despite the access to life cycle data for an increasing number of building materials, there are still numerous materials and recycling processes for which data are not available.

In addition, available life cycle data are nearly always site specific and reported emissions are mainly connected with energy use. The energy source used varies between different producers of today and between the produce of today and those of tomorrow. So does also the efficiency of the industrial processes. It can be easily shown that just by changing the energy source, the contribution to global warming can actually be changed by a factor of one hundred. The efficiency of the industrial processes is on the other hand not likely to vary much. As the questions in this study are general in character, a presentation of the contribution to different environmental categories based on site-specific data will be misleading.

From a study on the future energy supply (Azar, 1998), it can be concluded that in the reasonably near future, all energy use will cause a considerable amount of non desirable environmental impacts.

For those reasons, lack of data (on the use of raw materials and on emissions) for many products and recycling processes, available data are mostly site specific and that all energy use will cause environmental impact, the study has been limited to energy.

Recycling and Recycling potential

Recycling is divided into

- | | |
|--------------------|---|
| Reuse | The material is used for about the same purpose as initially. Reuse might imply upgrading or some renovation. |
| Material recycling | Recycling where the material is used as raw material for new products. |



Combustion Combustion with energy recovery. The energy saving from combustion is assumed to be the calorific value less energy for the recycling processes.

The recycling potential of a building can, as mentioned earlier, be briefly described as a way of expressing how much of the embodied energy and natural resources used in a product could, by recycling, be made useable after demolition.

Recycling potential has been defined as

the environmental impact due to the production of the material for which the recycled material will be a substitute, less the environmental impact of the recycling processes and associated transport.

The recycling potential will be further described in Chapter 6.

In order to define the recycling potential of a product, available recycling techniques and their energy requirement must be known. Further, the possibilities of dismantling, the amount of material to be assigned to each form of recycling, and the remaining service life time of the recycled product, must be assessed.

3.3 Limitations

Recycling is part of sustainable building. The research focuses on issues related to environmental and technical possibilities through recycling building materials used for houses. Other issues related to environmental design are not treated.

As regards recycling, the studies are limited to recycling of building materials and components after these have been dismantled in a refurbishment of the building or in the final demolition of the building. It does not include a reuse of the building itself. This means that measures taken in designing the layout in order to make the building more flexible for future use, or use of the building for new activities, is not dealt with.

The study is mainly limited to energy for the reasons given in the section *Energy use as an indicator of environmental impact* above. The environmental impacts of emissions to air, water and soil (other than waste) are not included. Nor are effects on the indoor climate or on the working environment included. Besides, factors as architectural value etc that will affect the willingness to recycle are not handled.



Recycling Potential and Design for Disassembly in Buildings

A decisive factor in our society is economy. The costs must always stay within agreed limits, and this plays an important part in decision making. However, the final costs for a specific process can to a great extent be a result of political decisions. In turn, political decisions are a result of political goals. Therefore, in an analysis of a system regarding its environmental *possibilities*, the costs should be excluded. Costs should only be analysed as a consequence. On the contrary, in an analysis of the environmental effects of a system, costs *have* to be included.



4 Recycling and environmental effects

In this chapter, the main benefits of recycling as well as different aspects of recycling will be presented. The chapter will start with a brief analysis of the supply of the most important resources used for building materials.

4.1 Why recycling?

The general environmental benefits of recycling are conservation of energy and of natural resources, reduction of emissions and reduced use of land for extraction of resources and for landfill.

The need for future recycling can, to some extent, be analysed by analysing the supply of resources. The four most important resources used today in the building sector are energy, gravel, timber and metals.

The full need for recycling can not be analysed in this way as the need for recycling is not determined only by the physical supply. For example, extraction of minerals for metal production is limited also by economic conditions and environmental impacts. When the availability of resources decreases, the need for energy use (which in turn causes environmental impact) and other environmental impacts will increase. When environmental impacts are considered, the physical supply will however be the primary limiting factor.

Energy

Numerous studies regarding energy use have been made of the supply and the assumed requirement in the future. The studies differ regarding time span, system boundaries, assumptions on global development etc. Despite the differences, a conclusion in common is that all energy conversion in a foreseeable future will be connected with undesired environmental effects. It can therefore be stated that there are strong reasons for measures which aim at reducing energy use.



Timber

In Sweden about 70% of the annual wood increment is felled today. This gives a potential for an increase in felling. However, the natural acidification of the soil increases with increased increment. In order to achieve the goals of the Swedish National Environmental Protection Agency regarding acidification and nitrification, a prerequisite is forestry adapted to the environment. This implies reduced demands on the wood increment.

In addition, to reduce the outlet of CO₂, performed scenarios show a conflict between the need for land in Sweden for food production and fuel production (Azar, 1998).

In a global perspective, there is also a conflict between the need for land for food production and fuel production. There is an intricate and complicated interplay of factors such as population growth, energy supply, economic development mainly in the poor countries, increasing part of animal feed among the world population etc. Analysis in a global perspective of the need for recycling of timber is therefore a very complicated issue.

Metals

The main metals used in the building sector are iron, copper, aluminium and zinc. The production of metals is very energy consuming.

Sweden is self-sufficient in iron and copper ore. The production of steel accounts for about 10% of the total Swedish CO₂ production.

Several studies have been carried out with the aim to assess the global reserves of different metals. However, such assessments involve several limiting factors. Examples of these are the patterns of consumption and demand which strongly affect the price, which, in turn, has an effect on recycling and development of substitutes. Consequently, as the result of a study will depend on the assumptions made regarding these matters, the result can vary considerably. For example, the assessment of the reserves of aluminium varies between 31 and 300 years in different studies (SNV, 1998a).

When the three aspects: (1) the difficulties in assessing the mineral reserves, (2) the energy used in producing metals and (3) attention to the precautionary principle, are combined, it is seen that there are good reasons for recycling metals.



Natural gravel

Natural gravel is a limited resource and very important for the supply of drinking water. With regard to the amount of gravel extracted in Sweden today, it is considered that the supply will run out in about 10-30 years in many regions in Sweden (SNV, 1998a). With regard to the supply of drinking water, the extraction must in some areas stop. A tax on natural gravel was therefore introduced in Sweden in 1995.

4.2 Definition of recycling

Recycling is here used as a generic term for different forms of recycling. The included forms of recycling are defined as follows (Thormark, 1995):

Reuse	The material is reused with the same function. For example a clay brick is reused as a clay brick.
Material recycling	The material is used as raw material in a new production process. Material recycling can be performed in open or closed loops. An example of open loop is gypsum plasterboard granulated and used as fertiliser. An example of closed loop is gypsum plasterboard granulated and used as raw material in production of new gypsum plasterboard.
Combustion	Combustion with heat recovery.

Material recycling is in this study mainly considered in closed loops, i.e. a product is recycled into the same kind of product as the original product. Open loops of material recycling are considered only for metals, concrete, lightweight concrete, clay bricks and glass.

4.3 Effects of recycling

As mentioned earlier, the general environmental benefits of recycling are saving of energy, saving of natural resources, reduction of emissions and decreased use of land for extraction of resources and for landfill. (An overview of the recycling possibilities for some common building materials as well as the energy saving through recycling is given in Thormark, 1997.)



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The benefits vary considerably with the form of recycling and with different materials. The environmental impact can actually even increase through recycling. Transport is mostly the major reason for the increase in environmental impact through recycling.

Transport can for specific materials account for a considerable proportion of the environmental impact. Transport must therefore be taken into consideration in order not to overestimate the benefit of recycling. The significance of transport depends on the gross energy saving, the weight of the material, the distance to recycling plant, the distance to raw material resource site and the transport logistics. The environmental impact of transport may be as much as the gross savings and may even turn the gross savings into increased environmental impact. But reduced need for transport because of recycling can also be the main cause of a considerable *decrease* in environmental impact. An example of this is recycling of concrete on site for use as coarse aggregate in roads as a substitute for gravel. (Torrington, 2000).

Parameters beyond energy use

It is here suggested that when the general recycling potential is assessed, energy is used as an indicator of the environmental impact (see Chapter 3).

When the effects of recycling are limited to energy, there are several important parameters that will be disregarded such as emissions to air, water and soil, noise, dust, working environment, use of resources, use of land area for extraction of raw materials and for landfill. Much research is in progress worldwide to develop methods for assessments of noise, dust, working environment, use of resources. For the moment, however, there is no obvious way in which these parameters are to be assessed.

Deconstruction, i.e. dismantling for recycling, is the best way of demolition in order to recycle. Noise and dust can then be considerably reduced compared with conventional demolition. On the other hand, recycling on site can result in an increase in noise and dust. An increase in noise and dust will e.g. occur when concrete is crushed on site.

As regards the working environment connected with deconstruction, few studies have so far been performed. In (Sternudd & Swensson, 1997, Miljo..., 1996) it was concluded that training and education of the workers are important in order to reduce the risk of accidents, to increase the motivation for the work and in this way also increase the efficiency of dismantling.

The effect on the use of land area for extraction of raw materials is a complex and difficult thing to assess. Besides, for the time being, available data give little information on this issue.



There is so far very little or no information on the specific effects on landfill from building waste. The assessment must be mainly limited to the amount put to landfill.

Emissions

When the effects of a specific recycling event of today are assessed, the emissions to air, water and soil have to be included. The emissions from processes can vary considerably. An obvious example is the energy source used in a process. A theoretical example limited to the energy use can be given to illustrate this. It is assumed that production of a product requires 100 MJ electricity, Swedish mix. To reuse this product, lorry transport, requiring 20 MJ, is needed. If the product were not recycled, a new product would have to be produced. The net result is then made up of the gain due to avoidance of production less the use of transport, i.e. a saving of 80 MJ. Regarding energy use, recycling can be concluded to be obviously beneficial. See Figure 4.1.

However, if emissions caused by the energy use were included, the result of this reuse would look quite different. The emissions contributing to four impact categories; global warming, acidification, eutrophication and photochemical oxidants, can be seen in Figure 4.2. Regarding these four impact categories, reuse is obviously not desirable.

Another example is reuse of wood. Assumed that the wood, unless reused, would be burnt with energy recovery. If the wood as a fuel source is replaced by oil, the emission of CO₂ would increase radically despite a fairly equal energy use.

Recycling Potential and Design for Disassembly in Buildings

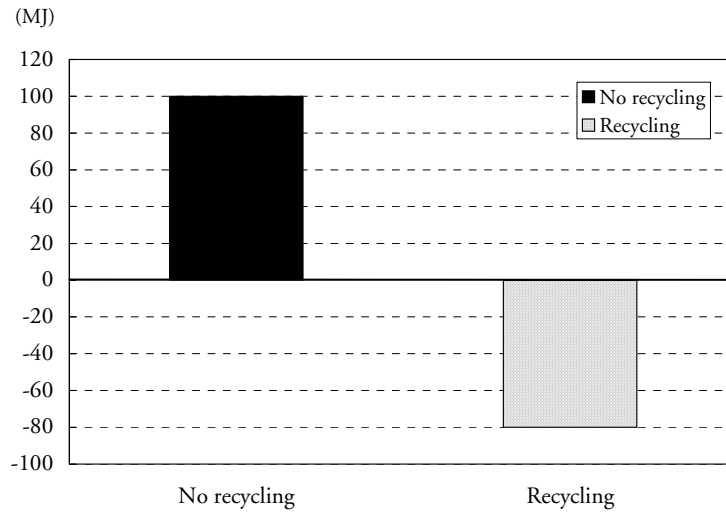


Figure 4.1 The result limited to energy use in the case with no recycling and the case with recycling. Negative value is an avoided energy use.

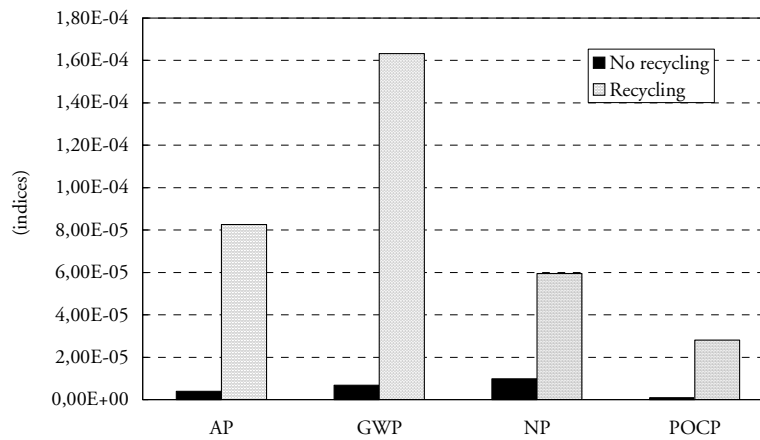


Figure 4.2 The result regarding the contribution to global warming (GWP), acidification (AP), eutrophication (NP) and photochemical oxidants (POCP) in the case with no recycling and the case with recycling. In the case with no recycling, the contribution is caused by energy use for producing a new product that is a substitute for the old one. In the case with recycling, the contribution is caused by energy use for transporting the product that will be reused.



4.4 Conclusion

It can be concluded that, assuming that these resources will be used in the future, there are strong indications for a reduction in the use of energy and for recycling materials made from wood, metal and natural gravel.

The main reason for economy in the use of both land and renewable resources is that the area of fertile land is limited. Besides, economic use of land and renewable resources is also necessary to preserve long-term and sustainable productivity of the soil and biological diversity.

When assessing the environmental effects of a specific recycling event of today, the emissions have to be included as transports can cause considerable environmental impact.



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5 Recycling in available assessment methods

This chapter will present some different tools and assessment methods for either choosing building materials or for assessing the whole building with respect to the environment. The tools and methods will be briefly described with the focus on how they handle aspects of recycling.

5.1 Introduction

The building process can be divided into different phases. In the different phases there is a need for simple tools for choosing building materials with respect to the environment or for assessing the whole building. The requirement for the tool varies depending on the phase and the player in the building process.

All tools will more or less be based on assessments, which in turn is impossible without including subjective judgements. Besides, environmental assessment of building materials and buildings is a very complex issue. Owing to the subjectivity and complexity in combination with the varying needs of the different users, numerous tools have been developed in the last ten years, or are under development.

The tools can roughly be divided into four groups; product declarations, eco-labelling, guidelines and building assessments.

In the following some examples from each of the four groups will be briefly described with the focus on how recycling is handled. The tools are often to some extent based on life cycle assessment, LCA, and a very brief description of LCA is therefore given. Some of the tools are not specifically developed for the building sector but provide a useable approach also for buildings.



5.2 Examples of approach to environmental assessment

The Natural Step

In 1989, an institute called 'The Natural Step' was founded in Sweden. The aim was to reach a consensus about the complex and diverging debate in society regarding environmental issues.

It was concluded that four basic system conditions would have to be fulfilled if the environment was to be preserved. The scientific justification of the underlying principles is presented in (Holmberg, 1995). The four system conditions are

- Minimal use of underground mineral deposits
- Persistent, artificial compounds must not be used
- The physical condition of the ecosystem must be preserved
- Energy use in society must be reduced.

No ranking of the conditions is given. The conditions are easy to understand and to follow as a general approach for the environmental goal of a building. However, they give little help in the everyday choice of building materials.

As regards recycling, the system conditions only say that recycling is generally good as it decreases the use of underground mineral deposits, provided that recycling reduces the energy use.

Life cycle assessment, LCA

Life cycle assessment, LCA, is a method for analysing the environmental impact of a product (or service) throughout its entire life cycle. (LCA is in this thesis described in Thormark, 1997b) The analysed life cycle usually includes the processes from extraction of raw materials up to final disposal. The environmental categories to be considered are the use of energy and resources, human health and ecological consequences. Several methods have been developed for the process of assessing collected data. LCA can be a powerful tool for comparison and choice of materials.

Recycling is a system where the 'waste' from one function (product) may constitute the raw material in a subsequent function. In LCA, the effects of recycling are handled through allocation. Allocation can be described as the process of assigning material and energy flows as well as the associated environmental discharges of a system to the different functions of that system. Several methods for allocation have been suggested.

The effects of allocation can be illustrated by a theoretical example of a steel beam. The beam is produced from ore based steel and is assumed to be reused after use. With available allocation methods, the minimum impact assigned to this beam will be the impacts from the dismantling processes needed to make future reuse possible, from upgrading processes and from transport connected with reuse. The maximum impact assigned to the same beam will be all impacts from ore based steel production, from the future waste treatment and all connected transport. A medium impact assigned to the beam is 50% of the total impact (from the ore based steel production, the dismantling processes, possible upgrading, future waste treatment and all connected transport).

My comment

In my opinion, available allocation methods are not really proper for products with a very long target life. If parts of the total impact is allocated to a subsequent function, no product is taking responsibility for these parts if no recycling occurs in future.

Besides, in (Thormark, 1997b) it was showed that some allocation methods will promote new products while other allocation methods will promote reused products. This can be regarded as a subjective element and the choice of method is then a manifestation of a valuation. In my opinion, this is especially unfortunate as the allocation is made in the life cycle inventory part of an LCA, which is commonly regarded as being objective. The same conclusion was expressed in (Trinius, 1999).

As recycling of building materials will take place in a distant future, if ever, the effect of recycling can only be considered to be a *potential* effect. With available allocation methods, this circumstance is concealed. The methods may to many people give an impression of being descriptive rather than being based on assumptions of the future.

Furthermore, available methods make it difficult, often impossible, to compare the effects from *different* recycling options.

My reflections on available allocation methods applied on buildings is also discussed in Appendix D.

5.3 Environmental product declaration

Environmental product declaration is a description of the environmental performance of a product, system or service over its entire life, from raw material acquisition, manufacturing and use to waste disposal and decommissioning.



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The Ecocycle Council for the Building Sector in Sweden, *Byggsektorns kretsloppsråd*, has developed a system for environmental product declaration of building products, Building Product Declarations (Byggvarudeklarationer, 1997). The stated purpose of the declaration sheets is to facilitate comparison of products from an ecocycle perspective in order to reduce negative environmental impacts.

The declaration sheet is mainly based on the ISO recommendations for Type II declaration (ISO 14021, 1999). The declaration gives information on the use of energy and raw materials, emissions to air, water and impacts on land connected with the various life-cycle stages of the product (materials content, production, distribution of finished product, construction phase, use phase, demolition and waste). Products are made comparable within a group of products by use of a functional unit. Presented impacts are not weighted against each other. The declarations exist in two alternative formats, one more simplified and the other more extensive in terms of reported information.

The Swedish Environmental Management Council, SEMC, is in charge of the Swedish system for third-party certified Environmental Product Declarations, EPD. It is performed as Type III declarations (based on ISO standards 14040-14043) and gives information on the same parameters as the Type II declaration. The declaration can also include information on materials content, recyclability and reuseability. Type III declarations are today only available for a few building products.

EPD declarations and building material declarations are based on an LCA. Recycling is thus handled through allocation (see above under LCA).

5.4 Eco-labelling

The purpose of eco-labelling is to provide information to the consumer regarding environmental aspects of a product. As the labels are addressed to the consumer, the information has to be very easy to understand. In Sweden there are today several eco-labelling systems, for example the EU eco-label symbolised by the EU flower, the Nordic Council of Ministers eco-label symbolised by the Swan, the the Swedish Society for nature Conservation (Svenska miljöskyddsföreningen) eco-label symbolised by Bra miljöval (Good Environmental Choice). Eco-labelling was initially limited to short-lived consumer goods.

The criteria concentrate on measurable impacts and impacts of major importance. The criteria can for example be the use of energy during production, the use of raw materials, the content of heavy metals, the



discharge of environmentally harmful components. With regard, for example, to environmentally harmful components, threshold values are often used as criteria. Criteria documents are available from the different institution/organisation.

As regards recycling, information is limited to whether recycled materials are used and whether the product is recyclable. The possible forms of recycling or the benefits of recycling are rarely presented.

5.5 Guidelines

Environmental preference method

The Environmental preference method was created in the Netherlands as a guideline for selection of materials for use in construction and refurbishment (Anink, 1996).

Products are compared within a product or construction group. For the product group 'Roof coverings' the guideline is: First preference: Timber shingles, Second preference: Clay or concrete tiles, Third preference: Fibre-cement slates, corrugated panels, bituminous slates. Not recommended: Zinc, copper.

The guideline is based on a life cycle perspective considering scarcity of raw materials, ecological damage by extraction, use of energy, use of water, noise and odour, harmful emissions, global warming and acid rain, health, risk of disasters, reparability, reusability and waste. Those reviewing the data make subjective decisions. Plus, zero or minus is used for each issue. The guideline gives no detailed description of how a specific product is assessed.

The guideline only states if a material is 'reparable' and 'reusable'.

The Folksam Environmental Guide

Folksam is a Swedish insurance company that has developed a guide to enable their clients to make an environmental assessment of building products.

The assessment is based on nine categories; whether the natural resource is finite, scarce or abundant, content of substances restricted by the Swedish National Chemical Inspectorate, working environment during production, working environment during building construction, waste during building construction, use phase, waste after use, whether eco-labelling is performed and labelled products are available. In the same way as in the Environmental preference method, the categories are judged



as ‘best choice’, ‘acceptable’ or ‘not recommended’. The assessments are summed up in a ‘final choice’, presented in the same way and based on subjective summation of the previous judgements. General background information on the criteria is available.

In this guide, the aspect of recycling is not included.

5.6 Building assessments

The development of methods for environmental assessment of *buildings* can be said to have started with three ground-breaking initiatives such as BREEAM (Prior, 1993), BEPAC (Cole, 1993) and LEED (US Green Building Council, 1996). The BREEAM and BEPAC methods were the only ones available when the work on this thesis started.

Numerous tools and methods have been developed since or are under development, for example Athena (Trusty, 1997), Eco-Quantum (Kortman, 1998), BEAT (Holleris-Pedersen, 1999), Eco-effect (Glaumann, 1999), Escalé (Chatagnon, 1998), Molca (De Hoog, 1998), BEES (Lippiat, 1998), Ecopro (Kohler, 1996a,b). The methods are essentially based on LCA.

The Green Building Challenge project, GBC, attempts to develop a second-generation assessment system in an international level for the first time.

In October 1998, an international conference known as Green Building Challenge '98, GBC '98, was held in Vancouver, Canada. The results of a two-year process of developing and testing an environmental performance assessment model, called Green Building Tool (GB Tool), were presented.

Building performance assessment tools have been adopted as effective measures to examining the environmental performance and energy efficiency of building and design. They are considered by researchers and government agencies as one of the best methods of promoting “Green Buildings” movement and performance. Besides, assessment are important measurement to educate the public in building environmental issues.

The development of building assessment methods is still in its infancy. There is no consensus on exactly what ‘Green Buildings’ are and there are many divergences on criteria included in different tools in different regions. The methods vary greatly regarding included aspects. Example of aspects sometimes included are economical aspects, indoor en-



vironment, working environment etc. The only method (at least to my knowledge) that clearly works with a 'recycling value-concept' is the Swedish Eco-Effect method which will be described below.

Eco Effect

EcoEffect is a Swedish method under development to calculate and assess environmental loads caused by a building during an assumed lifetime. It is developed for persons who plan, manage or use the built environment and need information on the environmental loads associated with this (Glaumann, 1999).

The assessment is based on use of energy and materials, indoor environment, outdoor environment and life cycle costs. LCA is used for the assessment of energy and materials. EcoEffect is the only method found that favours the use of both recycled and recyclable materials and components.

Reused building materials are considered as 'free', i.e. they are only assigned the impacts from upgrading and transport.

Recyclable materials are assigned a 'recycling value'. The recycling value is defined as impacts from the production of the material for which the recyclable material will be a substitute, less impact due to the recycling processes and transport. This value/impact is then subtracted from the value/impact of the production and the sum of this subtraction is presented.

My comment

There are several similarities between the way recycling is handled in Ecoeffect and the recycling potential in this thesis (the recycling potential will be described in chapter 6.).

In Ecoeffect the term 'recycling value' is defined in the same way as the recycling potential was defined and used in (Thormark, 1996, 1997a, b). The recycling potential for combustion of a material was there defined as follows:

The recycling potential for combustion of a material is equal to the energy required to produce the fuel for which combustion (with energy recovery) of the recycled material will be a substitute, less the energy required to make the recycled material suitable as a fuel.



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It should be noted that with this definition, the energy for production can not include feedstock (the heating value of the material). As feedstock is not included, it has to be dealt with as a use of resource, i.e. the *amount* of used timber, oil etc. Consequently, the use of resources must be taken into account in another way.

In this thesis the feedstock is included in the embodied energy. This is a simplified way to pay attention to the use of resources. This is the method mostly used in studies of embodied energy. However, there are other methods and this issue will be discussed below in Chapter 10, Discussion.

The recycling potential for combustion of a material is then defined as the calorific value of the material less the energy required for making it suitable as a fuel. (The recycling potential is described below in Chapter 6.).

It should be noted that if the recycling potential is limited to energy, those two ways of defining the recycling potential for combustible materials will have a considerable influence on the result. The influence on the result for a low-energy house (Appendix E) and for the building waste produced in Sweden in 1996 (Appendix F) is shown in Table 5.1. The recycling potential was in both cases calculated for two scenarios; Maximum material recycling/combustion, maxR/C, and Maximum reuse, maxReuse.

Table 5.1 The influences on the recycling potential (in percentage of the embodied energy) of two approaches of the feedstock. Two cases are presented; a low-energy house and the building waste produced in Sweden in 1996. Two scenarios are presented for each case; Maximum material recycling/combustion, maxR/C, and Maximum reuse, maxReuse.

	Building waste 1996		Low-energy house	
	maxR/C (%)	maxReuse (%)	maxR/C (%)	maxReuse (%)
Feedstock included	52	61	38	42
Feedstock excluded	30	45	15	23



Recycling in available assessment methods

Another difference between EcoEffect and the recycling potential approach is, that in EcoEffect the recycling value is subtracted from the production value. For reused materials it may result in a negative value which is not accepted. If the recycling value is greater than the production value, the recycling value is set to zero.

In the recycling approach in this report, no subtraction is made. The production value and the recycling value are presented separately. The recycling value can therefore be accepted to be larger than the production value. This provides the possibility to fully express the recycling potential for reused materials. (This is further discussed below in section 6.2.)

In Ecoeffect, two scenarios are used; the 'probable scenario' and the 'desirable scenario'. In the 'probable scenario' the probability of future recycling has to be defined. So far this is not done. In this report (as earlier in Thormark, 1996, 1997a, b) also two scenarios are used; the scenario 'maximum material recycling/combustion and the scenario 'maximum reuse'.

The 'desirable scenario' in Eco-Effect, and the scenario 'maximum reuse' in this thesis, are likely to be equal. The 'probable scenario' and any of the scenarios in this thesis are also likely to be the same, assuming equal values for the probability factor and the uncertainty factor.

Environmental status method (Miljöstatus-metoden)

When the Ecocycle Council for the Building Sector, *Byggsektorns kretsloppsråd*, was formed in Sweden, a number of Swedish companies took the initiative for a common assessment of buildings. This resulted in the Environmental status method. The intended users of an assessment are building managers, insurance companies, contractors etc.

The assessment includes a great many aspects such as energy use, indoor climate, noise, technical status, presence of hazardous materials etc. All assessments are scored one to five.

In the method, recycling is assessed in terms of household waste and the possibility of disassembly. The possibility of disassembly is assessed for structure, facade and roof. The score five is given to constructions assessed as 'easy to disassemble' and score three for 'normal' ease of disassembly.



5.7 Conclusions

It can be concluded that the aspects of recycling and/or the use of a 'recycling value' are as yet not generally included in assessment methods. However, from both the general discussion in society during the very last years and from discussions and proceedings at international conferences, it is obvious that this is an issue of increasing importance. Endeavours to include aspects of recycling and a 'recycling value' in assessment methods can therefore be expected to be increasingly discussed in the future.

There is no evident way of how to include a 'recycling value' and how to give credit for the use of recycled materials, recyclable materials and constructions suitable for disassembly.



6 The recycling potential

This chapter will present the theoretical principles of the recycling potential concept. Important parameters that have to be included will be discussed as well as some basic difficulties and weaknesses with the approach. The difficulties in predicting the future will also be discussed. The major part of the chapter is also presented in (Thormark, 2001).

6.1 Introduction

The difficulties in predicting the future recycling

Whether a material or component will be recycled in the future is dependent on a great number of factors. Many of these factors, in turn, influence or contradict each other. Besides, the probability of each factor is very different. Together the factors make up a complicated system. Part of this complexity is illustrated in Figure 6.1. From the figure it can be concluded that it is more or less impossible to predict future recycling.

A fundamental question regarding the amount of recyclable materials that will be produced in the future is the number of buildings that will be demolished. This will to a great extent depend on how 'old' buildings, components and materials are regarded. If old buildings are highly valued, they will be restored instead of demolished and the amount of recyclable material will *decrease*. On the other hand, the reuse of valuable and actually dismantled components will *increase*. With regard to the environmental effects, these two factors can be regarded to coincide, as reuse of buildings is, in general, the most valuable form of recycling.

It seems reasonable to assume that the faster changes take place in society, the more 'old' things will be valued. Old things have a tendency to become a symbol of safety and security.

The factors in Figure 6.1 can be divided into the *need* for recycling and *performed* recycling. Even if we can predict that there will be a future *need* for recycling, recycling might still not occur due to several other factors.

Any prediction of future recycling will be afflicted with considerable uncertainty. Moreover, the probable form of recycling is likely to vary greatly with different materials. Consequently, prediction of recycling is very difficult and prediction of the specific form of recycling is even more difficult.

Instead of making predictions of future recycling, future recycling could be expressed in terms of a *potential* for recycling.

In this study, the environmental benefits of recycling are mainly limited to energy use.

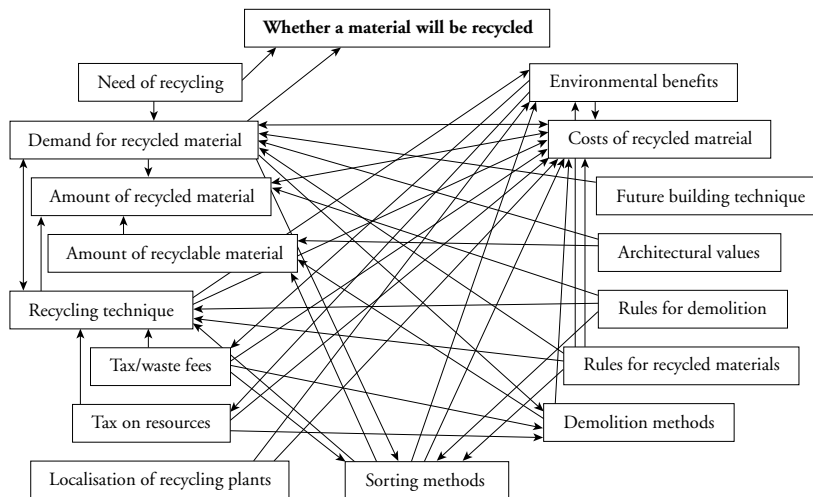


Figure 6.1 Some of the factors that together affect whether or not a material or component will be recycled in the future.

6.2 The principle of the recycling potential

The aim of the following sections of this chapter is to present and further discuss the concept of recycling potential. The recycling potential has earlier been discussed in (Thormark, 1996, 1997a,b).



The recycling potential

The recycling potential, R_{pot} , is a way to express how much of all embodied energy and natural resources, used in a building or a building element could, through recycling, be made useable after demolition. R_{pot} for a building can be calculated as

$$R_{pot} = \sum_{i=1}^n I_{pw\ i} \cdot Lt_i - E_{rec.\ proc\ i} \quad (6.1)$$

where

- n is the number of materials.
- i material number.
- I_{pw} is the environmental impact due to production of the material *for which the recycled product will be a substitute.*
- Lt is the remaining lifetime of the recycled material as a percentage of the predicted lifetime of the material for which the recycled material will be a substitute.
- $E_{rec.\ proc}$ is the energy use in all recycling processes, i.e. additional energy use in demolition needed to make future recycling or re-use possible, the energy use in all upgrading or recycling processes as well as transport from the site which it is supposed to be delivered from

For combustible materials, the energy saving is assumed to correspond to the heating value of the material. In the case studies, the recycling processes for combustible materials, except for untreated wood, were only taken into account as energy for transport to incineration plant. Untreated wood can be converted into wood chips and this process was taken into account. The energy use for this process is about 4% of the calorific value (Nutek, 1996).

In order to assess the recycling potential of a product, available recycling techniques and their energy requirement must be known. Further, the scope for dismantling and the amount of material to each form of recycling and the remaining service lifetime of the recycled product must all be known. Besides, the number of recycling loops must be defined.

In order to avoid extensive speculations on recycling in a distant future, it is here suggested that only one recycling loop should be considered. This will affect different materials differently. For example, metals can actually be recycled numerous times. The problem of how many recycling loops to include has to be discussed further.

The recycling potential can be used for example in the design process of new buildings, in the building code, in government subsidies to buildings fulfilling certain requirements regarding the potential of recycling



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(for example through tax reduction during the first years of a building's life time), in the planning of a demolition etc. A further description of its use is given in appendix D.

The recycling potential can be divided into a general, global level and a local level. A general level is valid when the recycling potential considers the future. A local level is valid when the recycling potential considers a demolition at hand. The recycling potential at a local level may vary between different regions as it is depending on locally available technology.

Allocation

Allocation can be defined as the process of assigning material and energy flows as well as the associated environmental discharges of a system to the different functions of that system. Recycling is a system where an allocation problem occurs, as the 'waste' from one function constitutes the raw material in a subsequent function.

If parts of the production and waste treatment are allocated to the recycled product, no product takes responsibility for these parts if no recycling occurs in future. (See also Appendix D.) My suggestion is that the following model should be tried:

- All impacts from production and waste treatment, I_{pw} , are treated as a separate quality allocated to the original product.
- The recycled product takes responsibility for the recycling processes.
- The potential benefits of recycling are treated as a separate quality, $R_{pot.}$

An advantage of treating I_{pw} and E_{rec} as separate qualities is that E_{rec} is made visible and that it facilitates an analysis of constructions. This is important as E_{rec} is so closely dependent on the construction, its connectors and its scope for disassembly.

This model has been applied in the case studies performed in this thesis.

Assessing the scope for dismantling

Assessing the scope for dismantling a construction and separating the materials from each other is important for the assessment of the recycling potential. Both separation of materials which disturb the recycling process and the amount of material discarded through dismantling need to be assessed. The importance will vary with the form of recycling. To assess the amount of material that will be discarded, is for example only important for assessing E_{rec} in a reuse-scenario.



An outline for this assessment will be discussed in the next chapter in connection with guidelines for disassembly.

Remaining service life time

The service life time and deterioration of a product are probably the most decisive factors for the assessment of sustainability and recycling. It has so far been difficult to find relevant data for life cycle assessment or the expected service life time for building materials.

Service lifetime can be divided into technical lifetime, economical lifetime and aesthetic lifetime. Which of these considerations will dominate will vary with different products. Whatever consideration is made, it will be connected with uncertainty and the uncertainty will of course increase with the applied time span.

Due to the difficulties of finding relevant data on the service lifetime, several projects have been initiated in Sweden. The Swedish Building Material Producers Assembly (Industrins Bygghmaterialgrupp) therefore initiated a survey on this issue in 1995. This initiative resulted in a preliminary report in 1999 (Burström, 1999). In that report, only the technical lifetime is considered.

An overview of the estimated service life of about 30 different components in a multi-family building built in Sweden 1999 is given in (Hed, 1999). Three different approaches were used in that study; dose-response, risk assessment and maintenance interval. The maintenance interval approach was used in most cases. It was concluded that to find and evaluate service life data was very difficult and time consuming.

In order to predict the reusability of a product, it is often suggested that if a product has been in use for a long time and is in good condition, the product is likely to be well suited for reuse. This is, however, connected with several problems that can be illustrated with old roofing tiles. How to relate the present quality of an old tile to its original quality, i.e. how to assess its decrease in quality? Is the expected environmental damage to a tile today and in the future, different from the damage up to now? How many of the original tiles on the roof have been replaced, for technical reasons, over the years? As can be seen, this method of assessing the remaining lifetime has to be used with caution.

Regarding new products, it is desirable that the producer would provide the needed information. Available information from the producer, however, does not, in general, include aspects of recycling.



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An introduction of an extended producer responsibility is likely to increase the information. For the moment it seems that the assessment of reusability has to be based on available information and available test methods combined with 'common sense', and performed with great caution.

In the case studies, reuse has been considered only when the technical quality of a material was assumed not to be negatively affected during the service life.

The degree of freedom

A quality so far invisible in the R_{pot} can be called *The degree of freedom*. It can be illustrated by two examples.

One example is *reuse* of beams. A wooden beam (solid wood, laminated wood, glulam etc), can be reused with great flexibility. Such beams can easily be shortened and can also be extended by joining two pieces. The same is valid for steel beams. Besides, wooden beams can be turned into fuel and steel beams can be turned into cars. A prestressed concrete beam, on the contrary, can be shortened but not lengthened. If the existing length is too short, downcycling is the only option left.

Another example is material recycling of metal products and mineral wool. A steel product can be remelted and turned into any other steel product. On the other hand, there is almost no other option for mineral wool than new mineral wool products.

From these examples it can be concluded that the probability of future recycling is very greatly dependent on the degrees of freedom. This quality could be made visible by introducing an uncertainty factor.

Comparison of objects

A problem that arises with treating I_{pw} and R_{pot} as separate qualities is whether or not I_{pw} and R_{pot} should be weighted together. If they are weighted together, how can a weighting be performed? In other words; how to compare buildings and how to tell which is the best one?

From the examples above of situations in which the recycling potential can be used, it is seen that it is first and foremost in the design process that a weighting is needed. In addition, government subsidies for certain types of buildings would probably be simplified if the two factors were weighted together.

Incorporation of the I_{pw} and R_{pot} in the building code can be done with or without weighting of the factors. If no weighting is performed, a maximum for I_{pw} and a minimum for R_{pot} , based on reference levels, can be used.

In planning a demolition, the problem of comparison is not relevant as only the R_{pot} of different demolition options is to be compared.

6.3 The problem to compare

Introduction

As just mentioned, a problem with the recycling potential approach is how to compare buildings and to tell which of the two buildings in Figure 6.2 is the best option. The problem is obviously caused by the fact that we can not predict the future and consequently we do not know whether or not recycling will take place. If recycling will take place, Building A is the best and if not, Building B is the best one. Assessed in view of this uncertainty, the two cases can be said to have different qualities, here called *IR*-factor.

The problem may partly and to a certain degree be tackled with the theory of probability. However, the problem remains if the probability is exactly the same in both Building A and Building B.

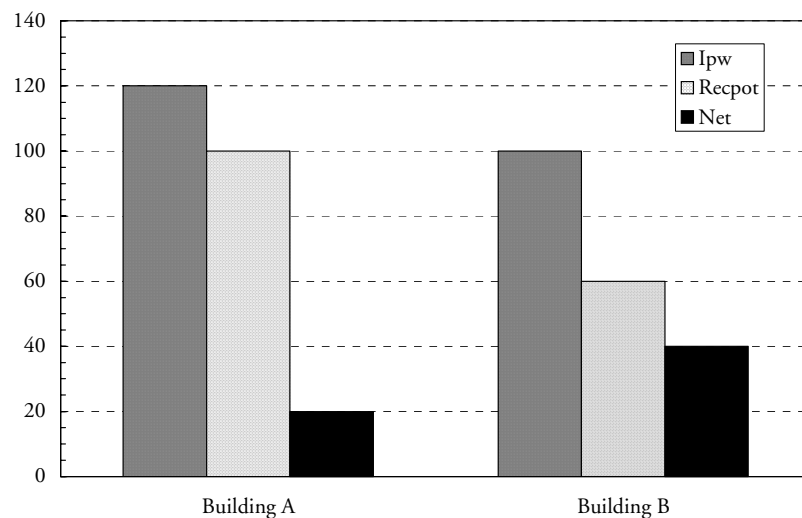


Figure 6.2 I_{pw} , R_{pot} and Net use in two cases. The question is which case is the best one?

When the problem is analysed it can be seen that the aim is to define the *IR*-factor in such a way that it will promote a building design that has



- low impact in production
- high potential of recycling
- low net impact whether or not recycling will occur

Further, it is desirable that calculation of the *IR*-factor from I_p and R_{pot} is an easy process not requiring extra tools.

Suggestion

The net energy use, *Net*, of a building can be expressed as

$$Net = \sum_{i=1}^n I_{pw\ i} - R_{pot} \quad (6.2)$$

where

n is the number of materials.

i is the material number.

I_{pw} is the environmental impact from production and waste treatment of the *initial* material.

R_{pot} is the recycling potential, defined above in equation (6.1).

It can be noted that *Net* can theoretically be a negative number. This could for example be the case for reused clay bricks. I_{pw} for reused bricks is very low as it consists of only dismantling, cleaning and some transport. If the bricks are laid with a mortar that permits a second dismantling, they can actually be reused again. From the definition of R_{pot} in equation (6.1) above, for reused bricks R_{pot} will be considerably higher than their I_{pw} , and consequently *Net* becomes negative.

If no recycling will take place, then $Net = I_{pw}$. The I_{pw} and the *Net* of a building can be marked on two parallel axes as in Figure 6.3. The x-axis can illustrate the uncertainty of recycling, u .

If a product has a minimum of I_{pw} and a maximum of R_{pot} the *Net* will be minimised and consequently the perpendicular line from the x-axis to the line between the y-axes will be minimised.

In this way, two objects can be compared by comparing the 'length' (can be a positive or a negative value) of the perpendicular line from the x-axis to the line between the y-axes, L , for each building. The 'length' of the perpendicular line can easily be calculated if the distance between the I_p -axis and the *Net*-axis is set to 1. In other words, the 'length' of the perpendicular expresses the *IR*-factor.

$$IR\text{-factor} = R_{pot} \cdot (1 - u) + Net \quad (6.3)$$

where

u is the uncertainty of recycling

The smaller the IR -factor, the better the product with respect to the relation between I_{pw} and R_{pot} .

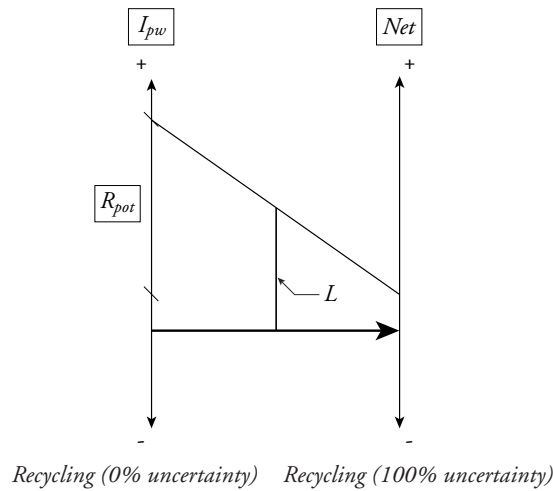


Figure 6.3 I_{pw} and Net are marked on two axes. The goal is to design a product with a minimum of I_{pw} and of Net . The IR -factor is expressed as the height of L .

As illustrated in Figure 6.1, there is a great uncertainty regarding future recycling. Even if all measures are taken to maximise recycling, future building technique, future architectural values and future demand for materials in other industry sectors. This uncertainty is likely to vary between different materials. In equation 6:3 above, u is aiming at this uncertainty.

6.4 Weaknesses, suggestions for improvement, questions

As mentioned earlier, determining the service lifetime of a product is probably the most decisive factor when assessing recycling. The greater the focus on recycling, the better data is likely to be provided. Limited access to data for the moment is not a weakness of the method in itself, even if it affects the result.



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Assessment of the scope for dismantling must for the moment be based on experiences from specific dismantlers and theoretical estimations. It would be desirable if in the future this information were provided by the producer. Both the scope for dismantling and the amount of material damaged by dismantling can then be assessed with better accuracy.

It is here suggested that only one recycling loop should be considered in order to avoid extensive speculations on recycling in a distant future. As mentioned earlier, this will affect different materials differently, and the problem of how many recycling loops to include has to be discussed further.

Questions

In the future, the benefits of recycling may be considerably different from today due to the future access to natural resources and future conversion of energy. As buildings have, or can have, a very long service life, recycling of building materials will mostly occur in a distant future. The benefits of recycling will then not go to the society of today but to the society of tomorrow. One central problem is then to define appropriate parameters to assess and measure. As the use of energy in a foreseeable future can be assumed to be connected with environmental impacts, energy seems to be a relevant parameter.

Regarding the suggestion that demands for recycling should be incorporated in the building code and in government subsidies for certain types of buildings, several questions can be raised. Firstly, can I_{pw} and R_{pot} be defined appropriately enough for such incorporation and subsidies? Secondly, is there a risk of an impoverishment and undesired simplification of the architecture or just a new challenge for better architecture?

These issues are beyond the scope of this study and they are therefore merely pointed out as issues that will have to be considered.



7 Design for disassembly and recycling

In this chapter, some general guidelines will be formulated for use in the design process of buildings, i.e. for architects and engineers. The guidelines are based on knowledge gained during the work and on results from the case studies. The chapter will start with a few words about design for disassembly in product design.

7.1 Introduction

Recycling is an important part of sustainable building and is desired when the product is to be exchanged. To avoid that a product will be exchanged, durability is an important quality, at least as long as it is not in contradiction to recycling. However, it does not matter how technically durable a product is if it is not also useable and desired. It is difficult to predict how a product will be valued in the future. To be usable and desired, flexibility is an important quality in order to correspond to new demands. But despite durability and flexibility, it may always come to a point when the product does not correspond to the new demands. Then recycling is the option.

The scope for recycling building materials/components in the future depends to a very high degree on how buildings are designed today. Design for disassembly and recycling is therefore a major contribution to increased future recycling. Disassembly has an important role not only in enabling parts and materials to be removed for recycling but also in enabling reconditioning, refurbishment, re-manufacture, repair and service of the product and components, thus extending their useful life.

In product design, the idea of recycling engineered products started in about 1990 (Simon, 1993). Research into Design for Disassembly is taking place at many Universities and companies throughout Europe and North America. Today, design for the environment and disassembly is



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well recognised, and also that this approach is economically beneficial. It is recognised that recycling of products is going to increase in the future and that it is necessary to design products that are environmentally friendly.

In order that multi-material products may be recycled, they must be dismantled. Design for Recycling, DfR, and Design for Disassembly, DFD, started in product design. Design for disassembly can be described as a design for easy disassembly of multi material designs (Luthrop, 1997). Design for disassembly developed from Design for assembly. The aspect of disassembly is added as a new dimension to the Design for assembly. Design for assembly is an established method in product design to improve assembly sequences for mechanical and electronic products. The goal for Design for disassembly is to find the correct borders between useful subassemblies. Computer tools for product design have been developed to simulate different disassembly and recycling scenarios by e.g. Luthrop (Luthrop, 1997).

Several methods of design for disassembly in product design have been developed, for example in (VDI, 1993, Dowie, 1994, Forss, 1994, Luthrop, 1997).

The guideline “Design technical products for ease of recycling” (VDI, 1993) was one of the first ones and is well known. It has become a standard when it comes to describing the goals and general rules for a recycling oriented design. In this document, the guidelines are classified into three distinct stages of recycling: recycling during production, recycling during the use of the product, recycling after the use of the product.

The guidelines in (Dowie, 1994) are classified according to three areas of product design; materials, fasteners - connections and product structure. In (Luthrop, 1997) the guidelines are based on identification of product structures and separating borders.

It can be argued that practical guidelines for design for disassembly can only be formulated within the framework of state of the art equipment manufacturing techniques and the economic realities of these techniques. Today there is very little such established practice, if any at all, within modern building construction. However, some general guidelines suitable for building design can be formulated based on general experiences from product design and general knowledge about building construction. Such general guidelines will be presented below in section 7.3.



7.2 Choosing the design goal regarding recycling

The form of recycling that will be possible in future is very greatly dependent on how the materials in a construction are connected to each other. This can be exemplified with a wall of clay bricks. If the bricks are laid with cement mortar it is impossible to dismantle the bricks, and reuse is not possible. Instead, the bricks can be crushed (material recycling) for use as coarse aggregate in roads. If on the other hand the bricks are laid with lime mortar, the wall will be easy to dismantle and the bricks can be reused.

There are considerable variations in the benefits of recycling between the different forms of recycling for different materials. This can be illustrated with aluminium and glass wool. The energy saving by material recycling is about 95% for aluminium while only about 5% for glass wool. This means that for aluminium, there is a rather small difference between reuse and material recycling. For glass wool, however, reuse is considerably better than material recycling. Consequently, in regard to energy alone, it is more important to overcome obstructions to reuse in the case of glass wool than aluminium.

Determining the recycling goal

The aspects of dismantling and recycling are rarely, if ever, included in the design of joints and connections today. To dismantle modern constructions can therefore be very time consuming, cause an unacceptable amount of damaged material, or simply be impossible. It is, however, the knowledge of those joints and connections that architects and engineers have in their toolbox when designing building constructions. To find joints that can be dismantled will therefore need some extra effort.

Therefore, a first step in a design for reuse/recycling is to determine what recycling form to aim at for the materials used in the construction. Which parts can be reused and which parts consist of recyclable materials? Which parts are hazardous? As a general rule, reuse is the best form of recycling. However, there may be a considerable or small difference in environmental impact between reuse and material recycling for different materials. At the same time, there may be considerable or small obstacles to achieving a feasible design for reuse. The question is then to determine when it is really environmentally worth while to overcome these obstacles. In Figure 7.1, a scheme is presented that will make this determination process easier. In the figure, there are three possible 'outcomes'.



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If the outcome is 'Recycling results in limited benefits', production of the proposed material has small environmental impact and recycling will have small environmental advantages.

If the outcome is 'material recycling/combustion', there is a relatively small advantage in reusing the component compared with material recycling/combustion. It should be noted, however, that for very energy intensive materials such as aluminium, scrap based production is still much more energy intensive than the production of a corresponding wood component.

If the outcome is 'facilitate disassembly for reuse', reuse is a considerably better environmental alternative than material recycling/combustion.

For this determination, information on and general knowledge of the following parameters for the materials is needed:

- use of raw materials
- energy use for production
- use of hazardous materials
- recycling options and their energy use

Clay bricks can exemplify the determination of the design goal regarding recycling. The product is energy intensive in production. The process from primary resource to raw material (here the production of clay) is considerably less energy-intensive than the process raw material to ready product (here burning the clay). The size of the brick provides nearly complete freedom in design. Using the checklist in Figure 1, it is clear that one really should strive for a construction that can be disassembled for reuse.

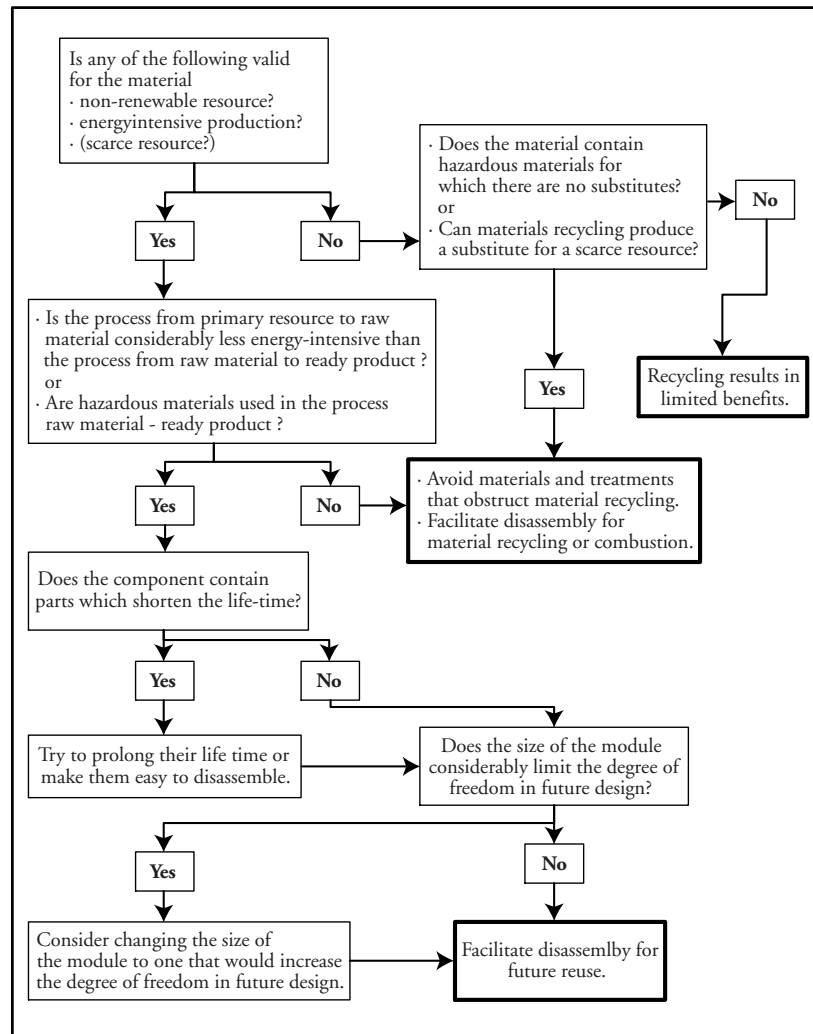


Figure 7.1 Questions to ask in order to determine what recycling form, regarding the environmental impacts, to aim at in the design for disassembly and recycling.

Available information

Information on most of these parameters (use of raw materials, energy use for production, use of hazardous materials and recycling options and their energy use), is today available for a large number of building products. To collect this information today is however rather difficult and time consuming. Such information ought to be provided by the producer and made available through a co-ordinated system.



To a certain extent such information is given in the building product declarations (described earlier in section 5.3). The declarations, however, give little or no information on recycling options and no information on the energy need for the recycling processes.

7.3 General guidelines for design for disassembly in building design

Introduction

The next step is to figure out connections and types of fastener suitable for disassembly. Design for disassembly enhances maintainability and serviceability of a product, and it enables recycling of materials, component parts, assemblies, and modules. The question is how to join and connect the materials to make up a building element.

A basic and general rule for all recycling is that the cleaner the material for recycling, the less energy will be needed in the recycling process and the better will be the quality of the final product. 'Clean' means here free from materials which complicate the recycling process or lower the quality of the recycled product.

If recycling is to be feasible, it is essential to be able to dismantle the building or building element quickly and efficiently. Further, the easier the dismantling and recycling process, the higher is the probability of recycling. The design factors found to be essential are time, cost, materials, energy, and modularity.

Handbooks, describing both good assembly and good dismantling methods in building science, would be useful.

Guidelines can be divided into design for reuse and design for material recycling/combustion. The following general guidelines are based on experiences from dismantling projects, recycling possibilities, results and experiences from the case studies and transformation of guidelines from product design.

Who is assumed to carry out dismantling

Whether it is a design for reuse or a design for material recycling/combustion, it has to be considered *who* can be assumed to carry out dismantling. Private persons, i.e. unskilled people without access to special tools, carry out some refurbishment. When it can be assumed that the material or component is likely to be replaced by private persons, the assembly



Design for disassembly and recycling

ought to be self-instructing regarding dismantling. Further, no special tool besides those which unskilled people can be assumed to possess ought to be needed for the disassembly.

Guidelines

There is a strong tendency in the building sector for the material producers to provide complete systems which include the material and associated products for the assembly. The design of an assembly suitable for disassembly appears to be a problem that is likely to be solved most appropriately by the material producers. Therefore the material producers ought to provide information on both disassembly methods and recycling options. Besides, they ought to provide information on materials for surface treatment etc that may disturb the recycling process.

However, there will always be situations when both architects and engineers need to find new ways of assembly. Therefore architects and engineers need both general and tangible guidelines for design for disassembly and recycling.

A very first measure on all levels, on the level of the general structure and on the construction and material level, is to consider how the material or component will be handled during use, renovation and deconstruction and to provide access for this.

Guidelines pertaining to disassembly and recycling can be structured in three groups; choice of material, structure of the building element and choice of joints and connections. A first set of rudimentary guidelines is presented in Table 7.1.



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Table 7.1 Guidelines for design for disassembly and reuse/recycling in building design.

Guideline	Reasons for the guideline
Choice of materials	
Choose recycled materials. Choose recyclable materials. Parts containing hazardous materials should be easy to remove. Minimise the number of different materials if they constrain the recycling process. Make inseparable parts from the same material or a material that does not constrain the recycling process. Code and mark all materials.	Stimulates the recycling market. Reduces waste to landfill. Increases the value of the product when it will be replaced. Facilitates elimination of hazardous parts. Simplifies dismantling and sorting. Reduces the need for dismantling and sorting. Simplifies the sorting and recycling process.
Design of construction	
Reduce number of parts. Modular designs will be easier to reuse. Pay attention to stability during dismantling. Design for serviceability.	Simplifies dismantling. Facilitates service and exchange. Dismantling is a reversed building process. Decreases disposal of non-functioning products.
Choice of Joints & Connections	
If two parts cannot be recycled together, make them easy to separate. Design to enable use of common hand tools for disassembly. Avoid adhesives unless compatible with both the parts joined together. Minimise the number of fasteners and joints. Fasteners and joints should be easy to locate, access and remove. Try to use joints and fasteners of material compatible with the parts connected. Pay extra attention to the consequences of joints and fasteners if the goal is design for reuse. Modular designs will be easier to reuse. Pay attention to stability during dismantling.	Simplifies the recycling process. Special tools may not be identified or available. Adhesives often cause contamination of materials. Simplifies dismantling. Facilitates the planning of dismantling and the dismantling process. Enables disassembly operations to be avoided Increases the amount suitable for reuse. Facilitates service and exchange. Dismantling is a reversed building process.



Documentation

For decisions in the future in regard to both the form of disassembly and the form of recycling, information will be needed regarding the materials used and the assembly techniques applied in a construction. Documentation of the building as well as of its changes over its lifetime is therefore important.

Principle changes from current practice

The principle changes between current practice and a design for disassembly and recycling can be summed up as follows:

- Life-cycle-thinking, i.e. to consider how the product is produced and how it will be handled during use, renovation and deconstruction and provide access for this.
- Design for disassembly and recycling.
- Ensure an extension of the multi-disciplinary knowledge in the design process.
- Provide information on the design to future users.

7.4 Assessment of the scope for disassembly

In the methods for design for disassembly in product design, evaluation of the scope for disassembly is often based on the time required for the disassembly. Technical issues, accesses to joints etc, affect the time required. The time is measured in case studies. Parameters that affect the time requirement are therefore important.

To base an assessment of the ease of disassembly of building constructions on the time requirement appears to be too limited for building constructions, and to measure the time requirement in case studies is mostly not possible. Besides, there are other parameters whose inclusion seems important, for example risks in the working environment.

One way to assess the ease of disassembly of a building construction may be to give scores for some important parameters. It is here suggested that the parameters to be assessed are risks in the working environment, time requirement, tools/equipment, access to joints and degree of damage to the disassembled material caused by the disassembly process. An outline of such a method is presented in Table 7.2.



Recycling Potential and Design for Disassembly in Buildings

The outline comprises several unsolved problems connected with assessment of an individual construction and comparison of constructions:

- How to define the criteria for each individual assessment?
- Should a construction fulfil a minimum level in each individual assessment?
- Should the parameters be weighted against each other and in that case, how should it be made?

Table 7.2 An outline of a method for assessment of the ease of disassembly of building constructions.

Goal for the disassembly	Assessed parameter	Assessment	Score
Reuse	Risks in the working environment	Big	1
		Small	2
		None	3
	Time requirement	Long	1
		Medium	2
		Short	3
	Tools/equipment	Advanced	1
		Simple	2
		Manual	3
	Access to joints	Very little	1
		Acceptable	2
		Good	3
	Damage to the material caused by disassembly	Very much	1
		Acceptable	2
		Very little	3
Material recycling	Relevant parameters.		
Combustion	Relevant parameters.		

7.5 Constraints and Contradictions

The question can be raised whether or not a design for disassembly and recycling will be inconsistent with other aims. Examples of other aims can be efficient building production, flexible use of buildings, prolonging the service life of a product or working environment. This question has not been systematically analysed but examples of observations made during the work will be presented below.



Design for disassembly and recycling

The likelihood that components will be reused will increase if the dimensions of the component do not decrease the degree of freedom in the future design. It is obvious that in some cases this can be inconsistent with both modern efficient building production and flexible buildings.

An example is prestressed concrete beams of very large span. Very large span decreases the freedom in future design considerably. On the other hand, a large span gives high flexibility and might prolong the possibility of using the building for other purposes than the original.

Another example is prefabricated storey-high wall elements. The elements represent efficient production but will also decrease the freedom in future design.

The scope for material recycling can be decreased by endeavours to prolong the service life of a product. An example is the widespread use of glass fibre fabric on gypsum plasterboard. With the technique of today, glass fibre fabric very greatly obstructs material recycling. On the other hand, in rooms exposed to high wear, the use of glass fibre fabric can considerably prolong the service life of a wall.

The abundant use of plaster and sealants is also an example of an efficient production that will make recycling more difficult. Plaster and sealants, the way they are produced today, will often contaminate the material and make dismantling and recycling more difficult.

In order to improve the working environment, gypsum plasterboards are now generally produced with a width of 900 mm instead of 1200 mm. This, however, may increase the use of studs, i.e. material use. The way the boards are joined to the studs also makes disassembly as well as reuse more difficult.



Recycling Potential and Design for Disassembly in Buildings





8 Discussion

This chapter will touch upon three issues; the significance of the applied methods for the results, the significance of the chosen case studies for the results, and recycling materials versus reuse of the building itself.

The significance of applied methods for the results

The essential matter in regard to how methods influence the results is how the use of resources was taken into account.

During the 1990s, the research community discussed different approaches to the development of methods for evaluating the use of resources and several approaches were presented. According to (Lindfors, 1995), all quantitative evaluation systems had data-gaps and there was only one system (the EPS-system) which considered non-energetic raw materials. Furthermore, in all literature it was recommended that, if assessment methods were used, more than one method ought to be utilised. As only one method seemed to be available, I thus decided not to use it.

In my case studies, the use of resources were instead taken into account in two different ways. In some of the case studies the conservation of resources were expressed in terms of energy. (Energy here includes all processes used to produce the final product from natural resources. For combustible materials, the feedstock energy was included and expresses the resource's value as a potential fuel.) This is the method mostly used in studies of embodied energy. In other case studies the conservation of resources were expressed in weight. Both methods are very simplified ways to pay attention to the use of resources.

However, in the course of my research, I started to reflect on the fact that actually neither of these two approaches, energy or weight, express any difference between scarce, renewable or non-renewable resources. In the last year I therefore again started to look for other methods to assess the use of resources.

There are today several methods available for assessing the use of both water, land, energy- and material resources.



Recycling Potential and Design for Disassembly in Buildings

In order to see to what extent the results would change when the use of resources was taken into account in different ways, three alternative methods were chosen and applied in one of the case studies in this thesis.

Assessing the use of resources

Resources are mostly divided into biotic and abiotic resources. (Biotic resources are objects derived from presently living organisms, for example wood, fish etc. Abiotic resources are coal, gas, oil, metal etc.)

The general and dominant approach in methods for assessing the extraction of resources is based on data for the reserve base. This is a common approach even if there are obvious problems to find relevant data in order to define the reserve bases, and also the reference area must be defined.

It can be pointed out that even if the reserve base approach is dominant, there are objections to this view. Julian Simon is a prominent spokesman of those who say that scarcity of natural resources is not a problem. Simon argues that, in the future, improved technology and potential substitution will result in us having all the raw materials we desire (Simon, 1996).

However, three established and widely accepted assessment methods were applied on a case study in this thesis, in order to see to what extent the results would change.

The case study dealt with energy and resource conservation through recycling the building waste annually produced in Sweden (Appendix F). In the case study, two recycling scenarios were compared to the recycling rates in Sweden 1996. The scenarios were maximum material recycling/combustion and maximum reuse. The three methods that were used were the EPS-system, the Eco-Indicator 99-system, and the UMIPsystem.

The EPS-system, Environmental Priority Strategies, is an evaluation system, developed in Sweden, in which the basic principle is to describe environmental impacts in terms of safe guards objects and value changes in them according to the willingness within the OECD countries to pay to restore them to their normal status (Steen, 1996). The EPS-system is the only found system that includes gravel. As has been mentioned in Chapter 4, gravel is considered as a scarce resource in Sweden.

The Eco-Indicator 99 method is developed in the Netherlands. In this method a damage function approach is introduced. The method only model mineral resources and fossil fuels. As more minerals and fossil fuels are extracted, the energy requirements for future extraction will increase. The damage is the energy need to extract one kg of a mineral in the future (Goedkoop, 1999).



In Eco-Indicator 99, model uncertainties, i.e. if the model is configured correctly, are coped with by cultural theory. With cultural theory the influence on the result from different attitudes can be showed (Goedkoop, 1999). When Eco-Indicator 99 was applied in this thesis, the hierarchical system was used. According to Goedkoop, the hierarchical system mirrors the common attitude in the scientific community and is the system suggested as the default method.

The UMIP-system, Development of Environment-friendly Industrial Products, is a Danish system for assessing the impacts on the environment from complicated industrial products (Hauschild, 1998). The amount of used resources in the product is expressed as the part of the total global available amount of that resource. The amount is then normalised and expressed in 'person-equivalents'.

Normalisation is an often used method for a further interpretation and discussion of impacts. In a normalisation, a given impact is related to the total magnitude of a given impact in some given area and time. Normalisation can be performed on a global scale or on a regional/national scale. Data on input or output can be divided by the number of persons in the relevant area, resulting in 'person-equivalents'.

Results

The results from the assessment of resource conservation in the case study, applying different methods are presented in Figure 8.1.

There is a great difference between the results from the EPS and the Eco99 method. This is due to different valuation of fuels respectively minerals in the methods. In the EPS-system, the use of copper and zinc is scored about 4000 times higher than the use of oil. In Eco99, the use of copper and zinc is scored only about 250 respectively 13 times higher than the use of oil.

It can be noted, that when resources other than fuel are higher valued than fuel resources, the difference between material recycling and reuse will decrease.

The main conclusion is that the embodied energy approach for assessing the recycling potential of building materials, will result in an outcome between the outcomes from several other assessment methods.

Thus, as the embodied energy approach is, compared to other methods, a very simple and fast method it appears to be sufficient for assessing the recycling potential at the design stage.

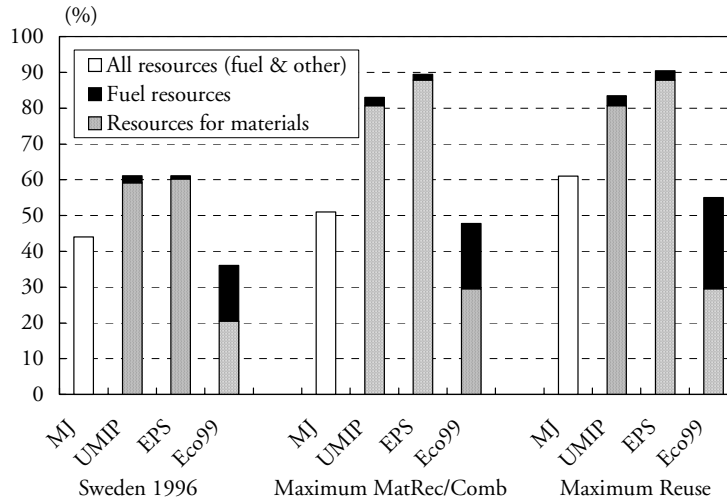


Figure 8.1. The conservation of resources with different assessment methods in three cases; Sweden 1996 and two recycling scenarios. The conservation of resources is expressed as percentage of resources represented by all materials released in 1996. MJ represents the conservation when resources are expressed in terms of energy.

The significance of the chosen case studies for the results

It can be asked to what extent the results from the case studies, performed on one-family houses, are valid for other types of buildings. Only multi-family dwellings and offices will be discussed here.

In both single-family dwellings and multi-family dwellings, the proportion embodied energy versus the energy for operation (space heating, hotwater, electricity for pumps and fans and household energy), is about the same (Adalberth, 2000). For a building life of 50 years, embodied energy accounted for about 15%. Moreover, the distribution on material categories are also about the same in single-family dwellings and multi-family dwellings. It is therefore reasonable to assume that the recycling potential will be about the same in both groups.

Regarding offices, studies on the significance of the energy need for operation versus embodied energy are rare. In a Canadian study of two offices, it was concluded that the embodied energy accounted for about 10-20% for a building life of 50 years (Cole, 1996). However, it was



deemed reasonable that the operation energy would be considerably reduced and that the embodied energy would then represent a dominant factor.

In Swedish offices, the energy need for heating is in general lower than in dwellings (Reference). This is mainly due to the heat contribution from electrical equipment.

There are more installations in offices compared to dwellings and offices are also more often rebuilt. The materials for installations are energy intensive to produce, are mostly produced from scarce resources, and have a high recycling potential. When offices are rebuilt, many of the building parts, for example internal walls, doors etc., are likely to be suitable for reuse.

Based on these circumstances, it can be assumed that the recycling potential in general is likely to be about the same or higher in office buildings than in dwellings. Design for reuse and disassembly is therefore probably more important in offices than in dwellings.

In the case study on annual building waste production in Sweden (Appendix F), the waste distribution on material categories was varied. In a parametric study, the distribution was the same as in materials used for new buildings and refurbishment in an average year during the period 1989-1995. The results show that wood and metal still make up for the dominating energy saving. The results also show an increasing importance of the reuse of mineral wool and gypsum plasterboard. However, the total energy saving decreased by about 50%. This is mainly explained by the expected decrease of wood. However, despite a different distribution on building waste categories in the future, the recycling potential will still be very high in the building waste.

Measurements for recycling materials versus reuse of the building

The question can be raised whether instead of design for disassembly, a design for flexible buildings and extended service life would be a more relevant issue.

Obviously, the most environmentally optimal solution is a flexible building designed for disassembly and recycling. However, there is no contradiction between flexible buildings and design for disassembly.



Conclusions

The assessed recycling potential in the case studies in this thesis are not overestimated. On the contrary, it may be underestimated. It seems quite reasonable to generalise the results from one-family houses to multi-family dwellings and offices. However, if the recycling potential is underestimated in general, it is likely to be especially underestimated for offices.



9 Conclusions

Introduction

The theoretical studies together with case studies have provided general knowledge regarding the importance of, and the scope for, recycling of building materials. Parameters such as the use of resources, the embodied energy in relation to the energy needed for operation, the inclusion of recycling aspects in the design phase, the forms of recycling, the system boundaries for analysis, transport etc affect the environmental impact of recycling.

The parameters are of different importance for different materials. In addition, the significance of each of the parameters varies for different materials, constructions and buildings. Some of the parameters are determined early in the design stage, which means that the environmental impacts will also be determined at an early stage.

Reasons to include aspects of recycling in the design phase

The way energy is produced today and will be produced in a foreseeable future, energy use will be connected with considerable environmental impact. The more the energy for operation will decrease, the greater will be the importance of the embodied energy for the total energy use over a lifetime. The embodied energy in general Swedish buildings accounts today for only about 15% of a building's total energy use during an assumed lifetime of 50 years. However, this figure has increased to about 40% in simple Swedish low energy buildings of today. Recycling of building materials can considerably decrease the total energy use. Therefore, the greater the share of the embodied energy in the total energy use of a building over its lifetime, the more important is the scope for recycling.

The design of a building, here the choice of material and construction, will affect the future scope for recycling. As we do not know about the driving forces of tomorrow, it seems reasonable to follow the principle of precaution. This implies the need to include aspects of recycling in the design phase.



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In the choice of the future environmentally best form of recycling, the main factor is the feasibility of disassembly. The possible forms of recycling in future are therefore mainly predetermined at the design stage. In view of this, the aspects of recycling need to be considered already in the design phase. It is therefore of great importance to pay attention to *both* the embodied energy of materials *and* to include the recycling aspects in the design phase of new buildings.

Inclusion of recycling aspects may lead to changes in surprisingly new areas. For example, large components might be efficient for the building process of today but will decrease the freedom of action in future use. Inclusion of future recycling in building design might therefore lead to new criteria for 'optimum-sized' modules. Another example is the foundation. The foundation may often account for a considerable part of the total embodied energy in a building. However, the general designs of the foundation provide a low recycling potential. The experience from projects when multi-dwelling blocks have been moved to a new site showed that the foundation accounted for the largest proportion of both costs and energy use. This indicates that it may also be of interest to develop and adapt foundations for efficient recycling.

It can be concluded that a new step in the endeavour to reduce the total energy use in the building sector will be to consider the aspects of recycling already in the design phase. An environmentally designed building is a building with low energy use in all phases and with a high recycling potential. The analysis of the total energy use of a construction and its recycling potential in different recycling scenarios can be a usable way of adapting constructions to recycling. Further, the recycling potential ought to be an integral part of an assessment method for buildings.

Benefits of recycling

Recycling of building waste can contribute to substantial conservation of both energy and natural resources. About 40-60% of the embodied energy can be recovered through recycling. Studies indicate that the recycling potential may be about 15% of the total energy use during an assumed lifetime of 50 years.

The best way to provide efficient recycling on a high level, i.e. without down-cycling, is to use recyclable materials and designs which enable disassembly and reuse. The proportions and kinds of natural resources that are conserved by recycling building materials vary considerably with the building material. They also depend on the resource that will be used as a substitute for the reused material.



Conclusions

The amount of waste to landfill is not always reduced by extended recycling if the region has a well developed system for handling of building 'waste'. Extended recycling may e.g. imply reuse of clay brick instead of crushing the bricks to coarse masses. Only the *form* of recycling is here changed and consequently the environmental benefits.

About 90% of the potential energy recovery can be achieved by material recycling and combustion. The potential of energy and resource conservation highlights the need for careful studies of the possibilities of increasing the recycling of building waste.

For some materials the results indicate that recycling yields very small benefits, or even increases the impact. Detailed studies of the recycling processes for those materials are needed in order to perform environmentally beneficial recycling. As regards energy conservation, the waste flow of today indicates that *reuse* of natural stone, clay brick and mineral wool and recycling of metal are the most important measures. Next to wood and metal, reuse of mineral wool accounts for an important and increasing share of the total energy conservation potential.

Reuse of clay brick materials in a building can contribute to a considerable reduction of the environmental impact of the building. However, the possibilities of reusing clay bricks in the existing building stock will decrease. This is due to the use of stronger mortar in brick constructions in younger buildings which often makes disassembly impossible.

Regarding conservation of natural resources through material recycling, metals and the materials that can be used as a substitute for gravel are the most important materials to recycle. Mass flow data in Sweden in 1996 indicate that crushed concrete, clay brick and lightweight concrete can meet the total need for gravel in new houses and in refurbishment.

Analysis of the recycling potential

The Recycling potential appears to be an important tool for expressing, measuring and comparing environmental aspects of buildings or building elements.

There is an increasing discussion regarding both the environmental and recycling potential and ways to make it visible. In developing assessment tools and guidelines, attention is paid to these issues.

So far very few case studies have been performed concerning the recycling potential. Owing to the complexity of the system and the long time span connected with recycling of building materials, simulations will have to be resorted to. In simulations there is always a need for simplifications, and simulations will therefore always involve a number of assumptions regarding uncertain circumstances.



Recycling Potential and Design for Disassembly in Buildings

Regarding the effects of recycling, which are a matter of use of resources and energy, an important issue is how to assess the use of different resources such as land, materials and energy. The results will obviously depend on the methodology used. This is important to remember when making decisions based on results.

Recycling of building materials affects a complex system. It can therefore be difficult to make broad generalisations of the environmental effects of recycling. Each material has to be assessed separately.

When the energy requirement for production and the recycling potential are studied, it is important to perform the studies on a proper system level. For example, all parts of the building envelope have to be studied at the level of the whole building. Further, materials have to be studied in complete constructions.

The importance of maintenance should not be neglected. Maintenance may account for about 15% of the total embodied energy of a new building. The importance will increase with increased service life of the building. Prolonging the lifetime of components/choosing materials with less embodied energy can decrease the part played by maintenance. The embodied energy, as well as the recycling potential, of materials/components which are assumed to have a rather short maintenance interval, is seen to be important.

An important issue regarding recycling of building materials is the transport distance and the transport logistics. The length of the feasible transport distance must be assessed in each case. The main factors that affect the reasonable distance are distance to the producer, the quality of the new material and all means of transport. When energy intensive and heavy materials from the local region are reused, however, there seem always to be considerable environmental effects.

To facilitate recycling in the future

Recycling of building materials/components in the future can be facilitated in the design stage by a design for disassembly and recycling.

The material producers ought to provide information on recycling options, disassembly methods and materials that will disturb the recycling process.

General guidelines for architects and engineers are formulated. The guidelines cover choice of material, design of the building element and choice of joints and connections. An important task is to consider how the material/component will be handled during use, renovation and deconstruction and to provide access for this. Making disassembly easy is



Conclusions

one of the most important measures to facilitate recycling. Disassembly also enables reconditioning, refurbishment, re-manufacture, repair and service of the product, which extend its useful life.

As disassembly is of crucial interest, the ease of disassembly of constructions has to be assessed and compared. So far there is only an embryo of a method for assessment of the ease of disassembly of constructions.



Recycling Potential and Design for Disassembly in Buildings





10 Future work to increase recycling

This chapter will point at several aspects that are important to develop in order to increase recycling and improve design for disassembly within the building sector.

Introduction

There are three processes that precede the actual recycling processes; design, construction and demolition. These processes are intimately interconnected. When it comes to recycling, the temporal sequence of these processes and the way they influence each other is often a question of 'the chicken or the egg'. In the cities, construction is often actually preceded by a demolition, i.e. construction starts with demolition. At the same time, the way the new buildings are designed may indirectly affect the way demolitions are performed. For example, the proposal for new buildings regarding the use of recycled materials/components, i.e. the demand for recycled materials, may decide how demolitions are performed. And vice versa, the way demolitions are performed and the materials are recycled, may affect the new design, i.e. the supply of recycled materials that can be used in new buildings.

This reasoning can be illustrated by an example. The demand is to a great extent influenced by the supply. If there is no supply of reused bricks, there will probably be no demand for them. At the same time, if there is no demand for reused bricks, there will probably be no supply.

A conclusion is that measures to increase recycling have to be taken in a lot of very different areas. Each area must take its own measures to increase recycling, without looking too much at adjacent areas.

This chapter will point at several aspects which are important to develop or in need of research in order to increase recycling and improve design for disassembly within the building sector.



Recycling Potential and Design for Disassembly in Buildings

The research on recycling has just started. A lot more work is needed to improve the recycling processes, the technology of assembly and disassembly. There is also a need to integrate extended aspects of recycling into methods for assessing buildings.

Several attempts were made to place these aspects in categories. On the other hand, as recycling and design for disassembly is a field with widespread implications and constraints, a really clear and logical structure was hard to find, if there is one at all.

Determining the environmental effects of recycling

The case studies in this thesis were mainly limited to the aspect of energy use. However, recycling has other environmental benefits like reducing the use of natural resources and the need of space for landfill. Recycling can also have negative environmental impacts such as noise, dust generation, vibrations etc. Consequently, further studies of the recycling potential ought to include more aspects than energy.

Environmental constraints on recycling must be investigated. There is for example limited knowledge today regarding environmentally hazardous materials that may leach out during the next use. An example is when crushed concrete contaminated with PCB (polychlorinated biphenyls) is used as coarse aggregate in roads.

Data

Regarding available recycling technology, there is a need for more process data.

Good availability of recycled materials is important for an increased demand. Systems for finding and offering recycled materials are under development and need to be improved.

More knowledge is needed about the expected service life time of products.

Recycling

In order to plan and increase recycling, there is a need for good methods and data to assess the amount of building waste that will become available. Better statistics are therefore needed on the mass flow within an individual building and within the building sector. The statistics need to be very transparent as the knowledge about environmental problems and the scope for recycling tend to change rapidly over time.

The way recycling plants are designed is important. Big plants may be more efficient but will make transport distances longer, and transport distances affect the environmental benefits of recycling. Big plants also



Future work to increase recycling

necessitate large investments and might give rise to inflexible systems which are difficult to change. Long distances will create a need for both intermediate storage at places far from recycling plants and good logistics for final transport. These questions need therefore to be analysed.

Combustible materials account for a large amount of the total building waste. To analyse the advantages and disadvantages of combustion is therefore important. A considerable extension of combustion capacity is needed if extended energy saving is to be achieved. In the study of the annually produced building waste in Sweden (Appendix G), only combustion and reuse of wood and combustion of plastics were assumed. Even if the combustion rate was halved in favour of material recycling, combustion would still account for a considerable part of the total energy saving. Besides, for some combustible fractions there is no other recycling possibility on hand today.

Combustion is a complicated problem that needs to be truly analysed. Combustion is always connected with undesired emissions. With increased combustion instead of other forms of recycling, there might be a risk of dependence on waste as a fuel. Further, the development of 'alternative fuels' might decrease if cheap energy from combustion is available.

Working environment

Good working environment and riskless deconstruction are important for increased recycling. The working environment connected with deconstruction and disassembly must be investigated. So far, very few studies have been performed on this issue (Sternudd, 1997, Miljo, 1996).

Assembly - Disassembly

There is a need to improve and develop methods and tools for disassembly. As a consequence of performed demolitions, several new tools have been developed. Examples are the tool 'Demon' for simplified removing of floor boards (Johnsson, 1995) and the use in Denmark of a vacuum cleaner for removing the plaster from boarded partitions.

The proportion of prefabricated concrete and lightweight concrete will increase in the future building waste. It is therefore desirable to analyse the possibilities of reusing prefabricated concrete elements.

Further research is of interest regarding the possibility of increasing the recycling potential by an advanced design for disassembly. In this context it is also of interest to study how much the embodied energy could be decreased by optimising the use of low energy building materials, and how this affects the recycling potential.



Recycling Potential and Design for Disassembly in Buildings

Techniques for efficient assemblies that provide easy and efficient disassembly need to be improved and developed. To a great extent this is an important task for the material producers.

A major measure to increase the scope for future recycling is to design for disassembly and recycling. Design methods for both building components and buildings are needed.

Test methods

Methods must be improved and developed for determining the quality of recycled building materials. Work has started to find methods for visual assessment of for example old clay bricks (Hansen, 1992), and structural timber (Holmqvist, 1998). Information regarding quality will have great influence on the demand for recycled materials.

There is also a need for methods; which can be used for materials prior to disassembly. For clay bricks, for example, it is important to assess the quality before starting deconstruction in order to decide the feasible disassembly method. Are the bricks good enough for reuse or is crushing for coarse aggregate more appropriate?

Costs

Fees and taxes can be used to direct the development in a desired direction. There is a need for a careful system analysis of all costs connected with recycling. Costs can both counteract and stimulate recycling. For example, the high cost of delivering unsorted building waste to waste plants may stimulate better sorting. On the other hand, high costs may also encourage dumping of unsorted waste in uncontrolled tips.

Other considerations

The environmentally best form of recycling is reuse of the building itself. It would therefore be interesting to perform studies regarding why buildings are considerably rebuild or demolished. This kind of information may be valuable in order to adapt buildings for reuse.

Methods for sorting and handling sorted building materials on the deconstruction site must be improved. Also in this area development has started. For example, new types of containers have been developed to facilitate sorting in several categories.

An important task is also to analyse whether or not any of the following issues will be inconsistent to each other: environment, recycling, working environment, production efficiency, economy etc.



Future work to increase recycling

Both attitudes and knowledge have been found to be of great importance for the final environmental impact of activities. Lack of knowledge may lead to objections to changes. One example is the common misapprehension that sorting is too time-consuming and causes too many problems because of the large number of containers for sorted materials. Interviews with firms which carry out a large amount of sorting show that they consider these objections are often due to lack of knowledge and experience. Education of all players in the building sector regarding aspects, possibilities and techniques is therefore necessary.

Besides the above measurements, there is also a need for considerable increased efforts from the public authorities. Research and information will have limited effects if not the public authorities show a strong interest in these issues and act powerfully. When laws, regulations and fees are thoroughly dealt with, they will probably be the most effective measurements for reducing the impacts from the building sector.



Recycling Potential and Design for Disassembly in Buildings





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ing waste and design for disassembly had become a more common subject in society. I really want to stress this, how fundamentally important the help from practitioners is for many research projects.

When all collected information was to be handled and analysed, I also had great and invaluable help from researchers, colleagues and friends at the department of Building Science, and at other departments at Lund Institute of Technology, Chalmers University of Technology, Royal Institute of Technology, SP Swedish National Testing and Research Institute, Danish Building and Research Institute, department of Geology and Mineral Resources Engineering in Trondheim and at many other universities and research institutes abroad. I really thank you all. To name specific persons is a mission impossible.

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Summary

Main conclusions

The general benefits of recycling are saving of energy, saving of natural resources, reduced environmental impact and reduced use of land for extraction of resources and for landfill. It can be concluded that there are strong incentives to reduce the use of energy and to recycle materials made from wood, metal and natural gravel.

Recycling of building materials can considerably reduce the total energy use within the building sector. The more the energy requirement for operation is reduced, the more important will be both the embodied energy and the recycling potential for the minimisation of the total energy use during a building's lifetime. The embodied energy in Swedish low energy buildings of today accounts for about 40% of a building's total energy use during an assumed lifetime of 50 years. Through recycling about 40% of the embodied energy can be recovered. The future scope for recycling is mainly predetermined in the design stage. A new task therefore is to consider the aspects of embodied energy and recycling already in the design phase.

About 50-60% of embodied energy can be recovered through recycling the annual building waste flow in Sweden. This is an increase of 20-40% from the level in the year 1996. Combustion with heat recovery and recycling of metal accounts for slightly more than 75% of the maximum potential energy saving.

The most important measures to increase the conservation of *energy* from recycling are increased combustion (or reuse) of wood, increased recycling (or reuse) of metal and reuse of clay bricks and mineral wool. Reuse of mineral wool accounts for an important and increasing potential of the total energy conservation.

As regards conservation of *natural resources*, metals and the materials that can serve as a substitute for gravel are the most important materials to recycle. Crushed concrete, clay bricks and lightweight concrete can meet the total need for gravel in new houses and in refurbishment.



Recycling Potential and Design for Disassembly in Buildings

At the end of the 1980s and during the 90s it was increasingly recognised that, besides the production phase, the use phase and the disposal phase are also very important for the total environmental impact of a product. This requires a new approach to product design. In the design phase, all the stages of a product's life-cycle must be considered.

Three different processes have together led and contributed to the development of recycling and design for disassembly in building design. One of these processes can be symbolised by Agenda 21, and comprises all environmental activities. The two other processes are the research tradition regarding energy use for operation and the activities with a view to reducing the costs caused by building waste. These processes have together played an important part in the development resulting in a matter of course with which both recycling and environmental aspects are handled today within the building sector.

When elements of these processes are combined, the obvious questions to ask are how to recycle, how to use recycled materials and how to design new products in order to facilitate recycling at the end of the life of the product/building.

Up to the present time, neither the aspects of recycling nor the use of a 'recycling value' have been generally included in available assessment tools. However, from both the general discussion in society during the very last years and international conferences, it is obvious that this is an issue of increasing importance. Endeavours to include both these aspects in assessment methods can therefore be expected to be increasingly discussed in the future.

The goal of this thesis was to provide an outline for a model to assess and express the recycling potential. (The recycling potential can be briefly described as a way to express how much of the embodied energy and natural resources can, through recycling, be made useable after recycling.) Another goal was to elucidate the environmental effects due to recycling of building waste. It was also a goal to provide general guidance regarding the aspects of recycling in the design phase.

The research work has been mainly performed through theoretical studies, collecting experiences from people in practical work and through case studies. The recycling potential approach as well as established methods of life cycle assessment have been used. In case studies the embodied energy of buildings was calculated and compared with the recycling potential in different constructions and recycling scenarios.

The studies have been limited to recycling of building materials. They do not deal with reuse of the buildings themselves. This means that measures taken in designing the layout in order to make the building more



Summary

flexible for future use, or use of the building for new activities, have not been dealt with. Nor are the effects on the indoor climate, on economy or on the working environment included.

Mainly because of the lack of data, the environmental impacts have been limited to embodied energy and use of resources. Owing to this limitation, there are several other important parameters that are disregarded, e.g. emissions to air, water and soil as well as noise, dust, working environment, use of land area for both extraction of raw material and for landfill. Much research is in progress worldwide in order to develop methods for the assessment of these parameters.

The suggested concept 'recycling potential' was, to a great extent, a result of my reflections on applying available allocation methods within the method of life cycle assessment of buildings. Besides, any prediction of future recycling will be afflicted with considerable uncertainty. Instead of making predictions of future recycling, future recycling could be expressed in terms of a *potential* for recycling.

An outline for assessing the recycling potential is suggested. In order to define the recycling potential of a product, the available recycling techniques and their energy requirement must be known. Further, the scope for dismantling, the amount of material to each form of recycling, the remaining service life time of the recycled product and the number of recycling loops, must be assessed.

A decisive factor for recycling is the scope for disassembly. Making disassembly possible is one of the most important measures to facilitate recycling of materials and component parts. Besides, disassembly also enables reconditioning, refurbishment, re-manufacture, repair and service of the product that extend its useful life, and it makes recycling possible.

Guidelines regarding disassembly and recycling can be structured in three groups; choice of material, structure of the building elements and choice of joints. A first step is to determine what form of recycling to aim at. In the future, decisions on both the form of disassembly and the form of recycling will need information on the materials and assemblies used in a construction. Documentation of a building as well as of its changes over its life-time is therefore important.

The principal changes between current practice and a design for disassembly and recycling can be summed up as follows:

- Adopt a life-cycle – approach. Consider how the product is produced and how it will be handled during use, renovation and deconstruction, and provide access for this.
- Design for disassembly and recycling.



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- Ensure that there is more multi-disciplinary knowledge applied in the design process.
- Provide information on the design to future users.

The design for disassembly and recycling can be inconsistent with other aims, e.g. efficient building production, working environment, flexible use of buildings or prolonging the product's service life.

Measures for increased recycling can be divided into two groups; recycling the waste of today and recycling in the future. Each group needs measures in a lot of very different areas. Each area must take its own measures to increase recycling without looking too much at adjacent areas.

Regarding the effects of recycling, an important matter is how to assess the use of different resources such as land, materials and energy. The results of a study will obviously depend on the methodology used. This is important to remember in decision making based on the results of studies.

Aspects of recycling need to be included in all methods and tools for the assessment of buildings and building products. The Recycling potential appears to be a usable approach for expressing, measuring and comparing environmental aspects of buildings or building elements.

It is hoped that the results of the work will contribute to discussions on how to define the recycling potential/value. It will hopefully also provide a basis for how to include recycling aspects in tools for the assessment of buildings, in the building code and in the production of building materials. Furthermore, the results will provide help regarding aspects of recycling for contractors in formulating building programmes and for architects and engineers in choosing materials and constructions.



References

- Adalberth, K. (2000). *Energy Use and Environmental Impact of New Residential Buildings*. Report TVBH-1012. (Doctoral thesis). Lund Institute of Technology, Department of Building Physics Sweden, Lund
- Agenda 21. (1993). United Nations, Department of Public Information.
- Anink, D., Boonstra, C., & Mak, J. (1996). *Handbook of sustainable Building*. London: James&James.
- Asplund, E. et al (1994). *Byggandet i kretsloppet*. (In Swedish). (Building in the ecocycle) Stockholm: Byggeförlaget.
- Azar, C. et al. (1998). *Energiläget år 2050*. (In Swedish.). (The energy-situation in the year 2050). Report 4894. Stockholm: Swedish Environmental Protection Agency.
- Brismar, C., & Lindhqvist, P. (1982). *Återvinning av byggavfall – en förstudie*. (In Swedish). (Recycling of Building Waste – a prestudy). Stiftelsen svensk återvinningsforskning.
- Bröte, S. (1998). *Disassembly systems : process analysis and strategic considerations*. LiU-TEK-LIC-1998:08. Linköping, Sweden: Linköping studies in science and technology.
- Burström, P-G. (1999). *Livslängdsbedömningar av byggnadsmaterial*. TVBM-7147. (In Swedish). (Assessments of the service life of building materials). Lund, Sweden: Lund Institute of Technology, Department of Building material.
- Byggsektorns Kretsloppsråd. (1997). *Miljöansvar för byggvaror inom ett kretsloppstänkande*. (In Swedish). (Environmental responsibility for building products in a ecocycle-perspective). Stockholm: Byggsektorns Kretsloppsråd.
- Byggvarudeklarationer. (1997). (In Swedish). (Building Product Declarations). Byggsektorns kretsloppsråd. Stockholm: Svensk Byggtjänst.



Recycling Potential and Design for Disassembly in Buildings

- Chatagnon, N. et al (1998). Escale, A method of Assessing a Building's Environmental Performance at the Design Stage. *Proceedings of Green building Challenge 98*, Vancouver, Canada, October 1998. Pp 195-202.
- Cole, R. et al (1993). *Building Environmental Performance Assessment Criteria: version1 – Office buildings*. Vancouver, Canada: The BEPAC foundation.
- Cole, R. et al. (1996). Life-Cycle Energy Use in Office Buildings. *Int. Journal of Building & Environment*. Vo. 31. No 4, pp 307-317
- Dowie, T., & Simon, M. (1994). *Guidelines for designing for disassembly and recycling*. DDR/TR18. Manchester: Manchester Metropolitan University, Department of Mechanical Engineering.
- Ecocycle Bill. (1993). Government Bill Laying down Guidelines for Ecocycle-oriented Development. Kretsloppspropositionen. (In Swedish). Proposition 1992/93:180. Stockholm.
- Eriksson, U. et al. (1974). *Transporter från byggarbetsplatsen. Special-studier av byggavfall*. (In Swedish). (Transports from the building site). Report R1:1974. Stockholm: Swedish Council for Building Research.
- Folksam's Miljöguide. (1997). (In Swedish). (Guide for the environment) Stockholm: Folksam.
- Forss, T. (1994). *Design Disassembly Fastening and Joining Methods in Plastic Engineering*. AFR-report 49. Stockholm: AFR Swedish Waste Research Council.
- Goedkoop, M., & Spriensma, R. (2000) *The Eco-indicator 99. A Damage oriented method for Life Cycle Assessment*. The Netherlands, Amersfort: PRé Consultants B.V.
- Glaumann, M. (1999). *EcoEffect. Miljövärdering av bebyggelse*. (In Swedish). (Environmental Assessment of Buildings -Environmental Load Impact during the Life Cycle of a Building.). Gävle, Sweden: Royal Institute of Technology, Centre for Built Environment.
- Hansen, H. et al. (1992). *En metode til bedømmelse af tegstens egenskaber ved hjælp af skærvefarven*. (In Danish). (A method for assessment the quality of clay brick from their colours). Danish Technological Institute, Murverkscentret.



References

- Hauschild M., & Wenzel H. (1998). *Environmental Assessment of products*. Vol 2. Technical University of Denmark, The Danish Ministry of Environment, Copenhagen.
- Hed, G. (1999). *Service Life Estimations of Building Components*. Report TR28:1999. Gävle, Sweden: Royal Institute of Technology, Centre for Built Environment.
- Holmberg, J. (1995). *Socio-ecological principles and indicators for sustainability*. PhD-thesis. Göteborg: Chalmers University of Technology, Institute of Physical Resource Theory.
- Holmqvist, C. et al (1998). *Återanvändning av rivningsvirke*. (In Swedish). (Reuse of timber waste from deconstructions) Nordtest project 1315-96. Borås, Sweden: Swedish National Testing and Research Institute (SP).
- Holleris Petersen, E. (1999) LCA Tool for Use in the Building Industry. *International Journal for Low Energy&Sustainable Building*. Vol 1, 1999.
- De Hoog, J. et al (1998). Evaluating Office Buildings with MOLCA (Model for Office Life Cycle Assessment). *Proceedings of Green building Challenge 98*, Vancouver, Canada, October 1998. Pp 71-78.
- Hägglov, P. et al (1978). *Återvinning av virkesspill från byggarbetsplatser*. (In Swedish). (Recycling of timber waste from building sites). Stockholm: Royal Institute of Technology, Department for building economy.
- ISO 14021. (1999). *Environmental labels and declarations - Self-declared environmental claims (Type II environmental labelling)*.
- ISO 14040. (1997). *Environmental management – Life cycle assessment – Principles and framework*.
- ISO 14041. (1999). *Environmental management – Life cycle assessment – Goal and scope definition and inventory analysis*.
- ISO/FDIS 14042. (1999). *Environmental management – Life cycle assessment – life cycle impact assessment*.
- ISO/DIS 14043. (1998). *Environmental management – Life cycle assessment – Life cycle interpretation*.
- IVA. (1974). *Rivning av byggnader*. (In Swedish). (Demolition of Buildings). Meddelande 186. Stockholm, Ingenjörssakademien.



Recycling Potential and Design for Disassembly in Buildings

- Jonsson, T. (1995). *Metoder och lönsamhet vid selektiv rivning Demon 93*. In Swedish). (Methods and profitableness by deconstruction). Stockholm : Byggeforskningsrådet: Byggdok.
- Jönsson, Å. (1998). *Life Cycle Assessment of Building Products*. PhD-thesis. Göteborg: Chalmers University of Technology, Department of Technical Environmental Planning.
- Kohler, N. (1996a). *EcoPro-manual*. Hinweise zur Benutzung des ECOPRO-Prototypen. (In German). Karlsruhe: Universität Karlsruhe, Institut für Industrielle Bauproduktion.
- Kohler, N. (1996b). *Methode zur kombinierten Berechnung v.Energiebedarf, Umweltbelastung und Baukosten in frühen Planungsstadien*. (In German). (Methods for combined calculations of energy requirement, environmental impact in early design stage) Karlsruhe: Universität Karlsruhe, Institut für Industrielle Bauproduktion.
- Kortman, J., & van Ewijk, H. (1998). Presentation of Eco-Quantum, the LCA-based computer tool for the quantitative determination of the environment impact of buildings. *Proceeding of the CIB World Building Congress 1998*. Gävle, Sweden.
- Larsson, B. (1983). *Materialförbrukning på byggarbetsplatsen*. (In Swedish). (Material use at building sites). Göteborg: Chalmers University of Technology, department for Building economy.
- Larsson, B. (1987). *Återvinning av byggavfall*. (In Swedish). (Recycling building waste) Reforsk 0284-996826. Malmö: FoU Stiftelsen REFORSK.
- Lauritzen, E. K. (1996). Genanvendelseindsatsen i bygge- og anlægssektoren 1986-1995. (In Danish). (Recycling in the building sector). DEMEX Rådgivende Ingeniører A/S, Miljøstyrelsen, Copenhagen, Denmark (in Danish). Reported in Overview of Deconstruction in Selected Countries. CIB Report ISBN 0-9643886-3-4, Publication 252, Chap. 7 by Lars Myhre.
- Linde, N. (1996). *Effektivare materialanvändning på byggarbetsplatsen*. (In Swedish) (More effective material use at building sites). Gothenburg, Sweden: Västra Sveriges Byggmästarförening.
- Lindfors, L-G. et al. (1995). *Nordic Guidelines on Life-Cycle Assessment*. Nord 1995:20. Copenhagen: Nordic Council of Ministers.
- Lippiat, B. (1998). *BEES 1.0. Building for Environmental and Economic Sustainability*. NISTIR 6144. U.S. Department of Commerce.



References

- Luttrop, C. (1997). *Design for disassembly. Environmentally Adapted Product Development Based on Prepared Disassembly and Sorting*. Doctoral thesis. TRITA-MMK 1997:5. Stockholm: Royal Institute of Technology.
- Miljo...(1996). Det genavendte hus. Part 6; Miljø- og arbejdsmiljøvurderinger. (In Danish). (The recycled house). Copenhagen: Miljø- og Ministry of Environment and Energy.
- Müller-Wenk, R. Depletion of abiotic resources weighted on base of "virtual" impacts of lower grade deposits used in future. Diskussionbeitrag Nr.57. Switzerland, Universität St. Gallen, Institute für Wirtschaft und Ökologi.
- Nielsen, P. et al. (1995). *Energi- og miljøanalyser af bygninger*. (In Danish) (Energy- and environmental analysis of buildings) SBI-meddelelse 108. Hørsholm, Denmark: Danish Building Research Institute.
- NUTEK. (1996). *Miljöanpassad uppvärmning*. B 1996:4. (In Swedish). (Environmental heating). Stockholm: NUTEK.
- Persson, J. (1995). *Selektiv rivning i Hallstahammar – demontering av miljonprogramhus*. (In Swedish). (Deconstruction in Hallstahammar). Stockholm: Byggbranschens forskningsstift. för arbetsmiljö.
- Persson, J. (1996). *Röda ladan*. (In Swedish). (The red barn). Falun, Sweden: Ekokultur förlag.
- Prior, J. J. (Ed.) (1993). *BREEAM 1/93- an environmental assessment for new offices designs*. Report No. BR 234. UK, Building Research Establishment.
- Sahlin, F., & Åhman, P. (1991). *Återvinning av restprodukter från byggarbetsplatser*. (In Swedish). (Recycling of waste products from building sites). Gothenburg, Sweden: Västra Sveriges Byggmästarförening.
- Sahlin, F. (1994). *Regler och teknik – Återvinning och hantering av bygg- och rivningsavfall*. (In Swedish). (Rules and techniques – recycling building waste). Stockholm: Maskinentreprenörerna.
- SBUF. (1990). *Bättre materialhantering på bygget*. Nr 90:20. Stockholm: Svenska Byggbranschens utvecklingsfond.
- Sigfrid, L. (1993). *Miljöstörande material i rivningsavfall*. (In Swedish). (Hazardous materials in building waste). Report 81. Malmö, FoU Stiftelsen REFORSK.

- Sigfrid, L. (1994a). *Byggskriningsavfall*. (In Swedish). (Building- and demolition waste). Report 112. Malmö: FoU Stiftelsen REFORSK.
- Sigfrid, L. (1994b). *Rivningsavfall – vilka möjligheter finns?* (In Swedish). (Building waste – which are the possibilities?) Lund, Sweden: Lund Institute of Technology, Department of Building economy.
- Simon, J. (1996). The Ultimate Resource 2. Princeton. Cited in Müller-Wenk, 1998
- Simon, M. (1993). In product design, the idea of recycling engineered products started about 1990.
- SNV. (1996). *Kartläggning av materialflöden*. (In Swedish.) (Survey of material flows). Report 4659. Stockholm: Swedish Environmental Protection Agency.
- SNV. (1997). *Sverige 2002*. (In Swedish). (Sweden 2002). Report 4747. Stockholm: Swedish Environmental Protection Agency.
- SNV. (1998a). *Betydelsen av begränsade globala naturresurser för Sveriges utveckling*. (In Swedish). (The signification of limited global resources). Report 4850. Stockholm: Swedish Environmental Protection Agency.
- Sternudd, C., & Swensson, L. G. (1997). Sten för sten... en selektiv rivning i Malmö. (In Swedish). (Brick by brick... a deconstruction in Malmö). Report TABK--97/3045. Lund, Sweden: Lund Institute of Technology, Department of Building Science.
- Thormark, C. (1995). *Återbygg*. (In Swedish). (Rebuild). Report TABK-95/3028. Lund, Sweden: Lund Institute of Technology, Department of Building Science.
- Thormark, C. (1996). Calculation of a Building's Recycling Capacity regarding Building Materials and Embodied Energy. In *Proceedings for the 1996 International Symposium of CIB W67*, pp 329-334. Vienna 4.-10. August, 1996.
- Thormark, C. (1997a). *Inclusion of Recycling in Life-Cycle Energy Use in Three One-family Houses*. Report TABK--97/7039. Lund, Sweden: Lund Institute of Technology, Department of Building Science.
- Thormark, C. (1997b). *Potential Energy Savings in Buildings Designed for Recycling*. Report TABK--97/3050. Lund, Sweden: Lund Institute of Technology, Department of Building Science.



References

- Thormark, C. (2001). Assessing the Recycling Potential in Buildings. In *Proceedings of the Task Group 39 Deconstruction Track, CIB World Building Congress, April 6, 2001*, Wellington, New Zealand.
- Torrington, M. (2000). *Recycling, Environment, Economics*. Proceedings from RILEM/ETNRecy Workshop, Paris 13-15.09 in 2000.
- Torrington, M. (2000). Management of demolition waste – using life cycle assessment methodologies. *International Symposium Integrated Life-Cycle Design of Materials and Structures. May 22-24, 2000, Helsinki, Finland*. pp 179-184.
- Trinius, W. (1999). Influence of Life Cycle Allocation and Valuation on LCA Results. *International Journal of Low Energy and Sustainable Buildings*, Vol. 1 1999.
- US Green Building Council. (1996). *LEED (Leadership in Energy and Environmental Design)*. Environmental Building rating system Criteria. + Green Building Rating System™, version 2,00. (2000).
- VDI. (1993). *Konstruieren recyclinggerechter technischer Produkte*. (In German) (Design technical products for ease of recycling.) VDI 2243. Berlin: Verein Deutscher Ingenieure, VDI.
- Warte, P. (1981). *Materialförbrukning på byggarbetsplatser*. (In Swedish). (Material use at building sites) Göteborg: Chalmers University of Technology, division for Engineering Logistics.
- Westman, P. (1993). *Konfektionerad isolering*. (In Swedish) (Precut insulation) Report 5270/1993. Lund, Sweden: Lund Institute of Technology, Department of Building Science.



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