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# Reuse of construction materials

- Environmental performance and  
assessment methodology

Liselott Roth



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Reuse of construction materials  
– Environmental performance and assessment methodology

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Department of Mechanical Engineering

Linköpings universitet

SE-581 83 LINKÖPING

Phone: +46 13 28 10 00

Fax: +46 13 28 11 01

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To  
Jonas and Hanna



## Abstract

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Reuse is a measure for resource-saving materials and energy use, which is stressed in the concept of *kretsloppsanpassning*, or societal industrial ecology (SIE), as it will be termed in this thesis. Reuse is here used as a general term for any kind of reuse and divided into recirculation, upgrading and cascading, according to the degradation of the inner material structure. Reuse of construction materials in society is mainly done with the belief that any kind of reuse is environmentally beneficial. However, this assumption is seldom critically assessed.

The aim of this thesis was to examine under which conditions reuse of construction materials in the Swedish building and transportation sectors is beneficial to the environment. In order to identify critical conditions, the environmental performance of actual building projects that to a large extent utilised reused building materials was assessed (Papers V-VI). To better understand the practice of SIE and how it was implemented, the transportation sector was studied (Paper I). In order to address the issue of assessing the environmental performance of construction material reuse, method development became an important part of this thesis. Methods and tools employed in this thesis were required to be able to simultaneously address different system boundaries and also involve simplification.

Studying the implementation of SIE revealed the lack of a holistic approach in environmental management, though it is present in the overall objectives of the SIE concept (Paper I). This was concluded by studying the energy and material stocks and flows in a life-cycle perspective in the environmental management of the Swedish National Rail and Road administrations. The study showed that the SIE-related measures implemented were outflow oriented, while the material inflows were generally quantified. Overall, the management and use phases were addressed, while the construction and deconstruction phases were poorly considered.

Studying environmental assessment methods showed that an important characteristic is the system boundaries, which to a large extent decide which issues could be addressed and what actually could be studied (Paper II). Environmental assessment methods applied to reuse of construction materials were organised in an assessment framework of four system levels: the material level, the local environment level, the narrow life-cycle level and the industrial system level. It was concluded that mainstream en-

environmental assessment of construction material reuse that is performed in the process of development consent and also in research, mainly addresses the narrow scope of the material level. In order to apply a holistic approach to environmental assessments of reuse of construction materials, the system boundaries needed to be widened.

When selecting system boundaries, methods and indicators, researchers indirectly decide on which environmental pressures we consider the most important (cf. Papers II - III). There are trade-offs between making broad or deep environmental assessments. To accomplish an environmental assessment wide in its scope requires abundant resources and is complicated to carry through. Simplifications of the complex reality are always needed. However, to counteract the risk of problem shifting, the simplified methods and indicators need to be balanced for environmental relevance and used with knowledge of what they reflect and what is left out (Paper III). One example of such method simultaneously environmentally relevant and capable to cope with wide system boundaries is the study of primary energy use in a life cycle perspective, applied to a material an energy use context (see Papers IV-VI).

In searching for a tool to prioritise building materials in building research and environmental management of the building sector, the total amount of building materials present in the Swedish building material stock was multiplied by their embodied energy coefficients (Paper IV). This product was normalized for the building materials' service life. The accounting resulted in an ordering of building material categories according to their energy intensity. These are, in decreasing order: wood materials, bricks and other ceramics, concrete and steel.

After calculating energy use in a life-cycle perspective for the recirculation, upgrading and cascading of larger building reuse projects of concrete and clay bricks, it is not self-evident that reuse is beneficial for the environment (Paper V, VI). It mainly depends on the use of auxiliary materials and their embodied energy, but also the primary energy use for the reuse processes, such as transportation distance and mode between the deconstruction and construction sites. In order to improve the environmental benefits of reuse, primarily the auxiliary materials used in current reuse projects should be minimised. Otherwise, there is a risk that the energy use for these materials turns reuse into an unfavourable process for the environment. Furthermore, reuse should preferably be environmentally assessed with a wide scope be-

fore implementation. What is included in such environmental assessment is significant for the outcome and the pictured environmental performance.

## Sammanfattning

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Återvinning är en åtgärd för resurshushållning och en viktig komponent i kretsloppsanpassningen av det svenska samhället. Begreppet återvinning kan användas som generell term för alla typer av återvinning. I den här avhandlingen delas återvinning ytterligare i direkt återanvändning (recirculation), materialåtervinning (upgrading) och degradering (cascading). Dessa typer karakteriserar till vilken grad materialet har återvunnits i relation till den nyproducerade produkten eller materialet. Det finns en allmänt utbredd tro på att återvinning är bra för miljön. Alltför sällan genomförs breda miljöbedömningar av återvinning som utreder under vilka förutsättningar detta gäller.

Syftet med den här avhandlingen har varit att studera miljöprestanda för återvinning av bygg- och anläggningsmaterial samt utveckla metoder för hur detta kan miljöbedömas. Studieobjekten var faktiska husbyggnadsprojekt där stora delar, särskilt stommen, av den nya byggnaden bestod av återvunnet material. I syfte att bättre förstå hur kretsloppsanpassning implementerats genomfördes en studie av kretsloppsanpassningen av transportsystemens infrastruktur som Banverket och Vägverket fått i regeringsuppdrag att genomföra. Metoder för miljöbedömning har prövats och jämförts, särskilt när det gäller systemgränser och vilken typ av miljöaspekter metoderna kan omfatta. En utgångspunkt var också att metoderna skulle vara relativt okomplicerade och rättframma.

Kretsloppsanpassningen av transportsystemens infrastruktur studerades med ett materialflödesperspektiv. Studien resulterade i en bild av att Banverkets och Vägverkets kretsloppsrelaterade miljöarbete saknade en konsistent hållning till att övervaka och styra förråd, in- och utflöden i infrastrukturens material- och energianvändning i ett livscykelperspektiv (Paper I).

Som ett resultat av olika studier med skilda systemgränser utvecklades ett ramverk för miljöbedömning av användning av restprodukter i vägkonstruktioner (Paper II). Ramverket kan användas för miljöbedömning av återvinning i allmänhet och sorterar miljöbedömningar efter systemgränser i fyra olika systemnivåer: materialnivån, den lokala nivån, begränsat livscykelperspektiv samt den samhälleliga nivån. Dagens miljöbedömningar av återvinning, i bland annat tillståndsprocesser men också i forskning, ge-

nomförs mestadels med snäva systemgränser som endast innefattar materialet självt, det vill säga på materialnivån. För att få en mer holistisk syn på återvinning bör systemgränserna vidgas och studier genomföras även på andra systemnivåer.

Att välja systemgräns, metod och indikatorer för sin miljöbedömning är delvis ett val av vilka miljöfrågor som anses viktigast (Paper II). Förenklingar och kompromisser är dock oundvikliga och innebär en risk för suboptimering. Det gäller därför att balansera förenklingar och val mot miljörelevans och analysera vad som innefattas och vad som exkluderas i miljöbedömningen (Paper III). Ett exempel på en sådan metod som samtidigt kan vara miljörelevant och vara applicerbar med vida systemgränser är att studera primärenergi i ett livscykelperspektiv i sammanhang där material- och energianvändning är relevant (se Paper IV-VI).

För att kunna prioritera vilka material som är viktigast i ett resurshushållningsperspektiv för materialanvändningen i byggsektorn beräknades den materialrelaterade energianvändningen (Embodied Energy) för det ackumulerade förrådet av svenska byggmaterial (Paper IV). Detta genomfördes för stora grupperingar av material och resultatet normaliserades med materialgruppens uppskattade livslängd. Detta resulterade i en indikator som pekade ut trämaterial som den mest energiintensiva materialgruppen, därefter tegelsten och andra keramer, betong och stål.

Miljöbedömning av direkt återanvändning av platsgjuten betong har givit delvis olika resultat beroende på valda systemgränser (Papers V-VI). De snävare systemgränserna i Paper V gav större energibesparing än de lite vidare systemgränserna använda i Paper VI. Det var tydligt från de studerade fallen att de alla var energibesparande jämfört med användning av nyråvara. Det är ändå inte självklart att återvinning av bygg- och anläggningsmaterial generellt är fördelaktigt för miljön; det beror bland annat på hur mycket kompletterande material som måste användas för att återvinningen ska kunna genomföras, transportavstånd mellan demontering och nybygge samt energiintensiteten i de material som används. Användning av kompletterande nyråvara beror bland annat på dagens byggnormer. För två av de tre studerade materialen var det tydligt att direkt återanvändning var mer energibesparande än materialåtervinning och ännu mer jämfört med degradering. Detta var tydligast för tegel, men också tydligt för prefabricerad betong. Alla typer av återvinning av platsgjuten betong var ungefär lika energibesparande som degradering av prefabricerad betong och tegel.



## Table of contents

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Abstract .....	5
Sammanfattning .....	8
Acknowledgement.....	13
List of papers .....	15
Other publications relevant for this thesis.....	16
Introduction .....	17
Problem definition.....	17
Aim of the thesis .....	20
Scope of the thesis.....	22
Theoretical framework .....	29
Environmental assessments with a systems approach.....	29
The Swedish concept of <i>kretsloppsanpassning</i> and industrial ecology .....	32
Reuse of construction materials in Sweden.....	34
Methodology .....	37
The research process and the papers .....	37
Missing the target? Implementation of industrial ecology in the Swedish transportation sector (Paper I).....	38
Environmental evaluation of reuse of by-products as road construction materials in Sweden (Paper II).....	39
Environmental relevance and use of energy indicators in environmental management and research (Paper III).....	39
Prioritizing building materials in environmental assessment of the Swedish building sector (Paper IV).....	40
Environmental analysis of reuse of cast-in-situ concrete in the building sector (Paper V) .....	40
Recirculation, upgrading and cascading of building materials. What is the difference? (Paper VI).....	41
Results from the papers.....	45
Missing the target? Implementation of industrial ecology in the Swedish transportation sector (Paper I).....	45
A framework for environmental assessment (Paper II) .....	46
Environmental relevance and use of energy indicators in environmental management and research (Paper III).....	49
Prioritising building materials (Paper IV).....	51

Environmental analysis of reuse of cast-in-situ concrete in the building sector (Paper V) .....	53
Recirculation, upgrading, cascading of building materials - What is the difference? (Paper VI).....	55
Synthesis.....	57
Assessment level .....	57
Issues addressed .....	59
Applied methods .....	59
Results of the studies.....	60
Discussion .....	61
Conditions influencing environmental performance.....	61
Reuse of construction materials in a life-cycle perspective .....	64
Conclusions .....	67
Future research .....	69
References .....	71
Personal communication .....	78

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Lastly, my family Hanna and Jonas, for bringing joy into my life, for supporting me in all situations and for their unconditional love.



## List of papers

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Attached to this thesis are the papers listed here, referred to in the text by their roman numbers.

- Paper I L. Roth & M. Eklund. (Manuscript) Missing the target? Implementation of industrial ecology in the Swedish transportation sector.
- Paper II L. Roth & M. Eklund. (2003) Environmental evaluation of reuse of by-products as road construction materials in Sweden. *Waste Management*, vol. 23, pp. 107-116.
- Paper III N. Svensson, L. Roth, M. Eklund, A. Mårtensson. (Accepted) Environmental relevance and use of energy indicators in environmental management and research. *Journal of Cleaner Production*.
- Paper IV L. Roth & M. Eklund. (Accepted) Prioritizing building materials in environmental assessment of the Swedish building sector. *Building & Environment*.
- Paper V L. Roth & M. Eklund. (2000) Environmental analysis of reuse of cast-in-situ concrete in the building sector. In: Shanableh A. & Chang W.P., eds. *Towards Sustainability in the Built Environment*. Brisbane, Australia: Faculty of the Built Environment and Engineering, Queensland University of Technology, pp. 234-243.
- Paper VI L. Roth & M. Eklund. (Submitted) Recirculation, upgrading and cascading of building materials. What is the difference?

Paper III was written together with Niclas Svensson, Mats Eklund and Anders Mårtensson. All of us contributed to different parts of the paper in the beginning of the process. However, the final work was done by Niclas Svensson together with me. Paper V was one of my first studies as a PhDstudent and the contribution from Mats Eklund to both the study and the paper was larger than in the recently written papers, Paper I, II, IV and VI, all of which were mainly written by me, yet thoroughly discussed with Mats Eklund.

## Other publications relevant for this thesis

- L. Roth & M. Eklund. (2001) A systems analysis approach to the study of environmental pollution in the road environment. In: The Swedish National Road and Transport Research Institute (VTI) & The Swedish Transport and Communications Research Board (KFB), *VTI konferens 16, 2001. Transportforum 2001. Sammanställning av konferensföredrag vid forskardagarna i Linköping 10-11 januari 2001. Transportforum 2001 D.1, Session 7*. Available at URL:  
<http://www.vti.se/EPiBrowser/Publikationer/K16del%201.pdf>
- L. Roth & M. Eklund. (2000) Concepts and goal definitions in implementation of societal industrial ecology in the transport infrastructure in Sweden. (In Swedish: *Begrepp och målformuleringar i kretsloppsanpassningen av transportsystemens infrastruktur*). KFB-meddelande 2000:17. Stockholm: The Swedish Transport and Communications Research Board (KFB). Available at URL:  
<http://www.kfb.se/publ/main.htm>
- M. Eklund, A. Lindqvist-Östblom, L. Roth, N. Svensson. (2000). Material flow analysis for environmental management in large technical systems. In: Shanableh, A. & Chang, W.P., eds. *Towards sustainability in the built environment*. Brisbane, Australia: Faculty of the Built Environment and Engineering, Queensland University of Technology, pp. 567-574.
- M. Eklund, L. Roth, N. Svensson. (1998) Environmental aspects of material use in the infrastructure - A manager's perspective. In: Kleijn, R., Bringezu, S., Fischer-Kowalski, M., Palm, V., eds. CML report 148. ConAccount Workshop. *Ecologizing Societal Metabolism. Designing Scenarios for Sustainable Materials Management*. November 21st 1998, Amsterdam: Centre of Environmental Science, Leiden University.

## Introduction

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This is primarily a short introduction of the problem studied, the aim and the scope of the thesis.

### Problem definition

*Kretsloppsanpassning* or societal industrial ecology (SIE), as it will be called in this thesis, is a Swedish phenomenon introduced by the Swedish government (Swedish Government, 1993). SIE is based on environmental concerns and aims at resource-saving materials and energy use. A central strategy to SIE is to close the material cycles through increased reuse. Reuse has attracted much attention in the societal debate, for example, through the ordinance on producers' responsibility, which for example, considers packaging waste and car tyres (Swedish Government, 1993). In the strategy for non-hazardous and resource-efficient (industrial) material cycles, the Swedish government emphasises that the potential benefits of using waste as resources should be employed as much as possible (Swedish Government, 2003b; Swedish Government, 2003a).

It is a common belief that SIE and reuse are good for the environment in all cases. Among the spokesmen for reuse it is not uncommon to meet the statement that any type of reuse is good for the environment and sometimes also becomes a goal in itself. As an example, the reuse ratio, which is not always clearly defined, is a commonly used indicator for building demolition projects. This involves the aggregation of information on various reuse measures of different material categories into the same indicator. A high reuse ratio is the goal, but it is often not obvious how it influences environmental performance. The European Council Directive on waste classifies any type of reuse of a product or material in the same category (The Council of the European Communities, 1991); thus not considering possible environmental differences among various reuse measures.

In society, environmental assessments of reuse of materials are, for example, performed when the reuse of materials, such as industrial by-products, are part of a project that requires permission according to the environmental code, such as rail and road construction. Even though, many different environmental pressures are dealt with within environmental impact assessments required in the process of development consent (Swedish Na-

tional Road Administration (Vägverket), 2004a, pp. 131-5), the decision-making authorities have traditionally focused the environmental requirements on the content of toxic substances, which are present in some industrial by-products, and the risk for leakage into the immediate environment. Despite the ambition to address a broad spectrum of environmental pressures, the decision criteria for material use assessment criteria in the *Handbook of EIAs within the Road Sector in Sweden* only address the use of natural gravel and chemical content. Also, the environmental decision criteria for the use of crushed concrete in road structures address the total chemical content and leaching behaviour (Swedish National Road Administration (Vägverket), 2004b). Similarly, a Norwegian decision-making method for reuse of materials in road construction addresses release of chemical substances and risk evaluation (Petkovic et al., 2004). Also, the Dutch building materials decree (DBM), mainly focuses on emissions from the materials and on pollution prevention. Despite a discussion of waste minimisation and reuse priorities in the judgment criteria for construction materials (Eikelboom et al., 2001), resource aspects are not included and therefore not assessed within the DBM-framework. Consequently, the required environmental assessments of reuse have mainly consisted of chemical analyses of the reused materials. This approach represents a narrowly conceived problem definition (cf. Ayres, 1994), in line with practice of environmental assessments for development consent as described by Bruhn-Tysk and Eklund (2000). Such an approach does not address the overall aim with reuse, which is to contribute to saving natural resources.

Much of the research focusing on environmental performance of reuse of construction materials deals with the material itself, including its chemical composition and leaching behaviour (cf. Fällman and Aurell, 1996; Fällman and Hartlén, 1996; Nunes et al., 1996; Tossavainen and Forssberg, 1999; Motz and Geiseler, 2001). This focus is underlined by one of the editors of the *International Journal of Integrated Waste Management, Science and Technology*, who writes that “Release of constituents through leaching is a key aspect for judging environmental impact of waste management options...” (van der Sloot, 2004, pp. 751-2). Another example comes from the latest RILEM conference (November 2004, Barcelona) on the use of recycled aggregates in buildings and structures, in which delegates mainly addressed leaching tests when referring to environmental assessments (Vázquez et al., 2004a; Vázquez et al., 2004b). A Swedish example is a recent report on the environmental evaluation of exterior building materials,

published by SP, the Swedish National Testing and Research Institute (see Gustafsson (2004)). This report is an overview of to what extent chemical substances could be released from exterior building materials (Gustafsson, 2004). It also addressed risk assessments. To sum up, the environmental performance addressed within these examples of research does not include the use of resources or pressures relevant on a regional or global scale.

Research dealing with environmental assessment methods applying a systems approach often discusses the importance of system boundaries (cf. Hertwich et al., 1997; Baumann and Cowell, 1999; Finnveden, 2000; Jönsson, 2000; Udo de Haes et al., 2000). In spite of this recognition, merely a few researchers apply a broader environmental perspective to the reuse of construction materials. However, there are some exceptions in the environmental building research area: Thormark (2000a); Thormark (2000b); Gao et al. (2001); Mroueh et al. (2001); Thormark (2001a); Brown and Buranakarn (2003); Venkatarama Reddy and Jagadish (2003). To conclude, there is a gap between the societal environmental ambitions of reuse and how reuse mainly is environmentally assessed by authorities and the research community. To bridge this gap and to environmentally assess reuse in a larger context, the importance of system boundaries in environmental assessments must be understood.

My ambitions with this thesis were to contribute to a broader basis for environmental assessments of reuse of construction materials and also to develop environmental assessments that could come in to use in society. Assessment methods that could be used in this context, for example, life-cycle assessment, material flow accounting and strategic environmental assessments, could be very complex and time-consuming. If environmental issues are to be an inherent part of management in industry and by authorities, a simplification would be preferable. Therefore, the methods addressed in this thesis were reduced and simplified versions of methods that could involve a wider systems perspective and at the same time address relevant environmental pressures.

To sum up, there is a gap in research considering the overall environmental performance of reuse of construction materials. Further, as economic resources are spent on the implementation of reuse processes in society in the name of their potential environmental benefits, reuse of construction materials becomes interesting to study from an environmental point of view.

## Aim of the thesis

The aim of this thesis was to examine under which conditions reuse of construction materials in the Swedish building and transportation sectors is beneficial to the environment. In order to identify critical conditions this included an examination of the environmental performance<sup>1</sup> of a few building projects that to a large extent utilised reused building materials (Papers V-VI). To better understand the meaning of SIE and how it was implemented, the transportation sector was studied (Paper I).

In order to address the issue of assessments<sup>2</sup> of environmental performance of reuse of construction materials, method development became an important part of this thesis (Papers II - IV). Methods and tools were required to simultaneously be able to cope with different system boundaries and also involve simplification. Especially emphasised was the importance of system boundaries and indicators for environmental pressure<sup>3</sup>.

This aim led to the following studies:

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<sup>1</sup> The term environmental performance is here used in a very wide sense; it could include both materials' characteristics that interact with the environment and environmental pressure during the materials' life cycle. Environmental performance could additionally encompass qualitative information on environmental issues in environmental management. For example, the scope of an environmental assessment represents the environmental impact categories considered important. Inclusion of an impact category does not necessarily mean improved performance but it is more likely than if not included in the assessment. This means that environmental performance is used in a wider sense than the definition in the ISO 14001 standard concerning environmental management systems. However, environmental performance as it is used here could, of course, coincide and overlap with the definition in ISO 14001, which is "measurable results of an organization's management of its environmental aspects" (ISO 14001:2004, 2004).

<sup>2</sup> Environmental assessment in the process of performing strategic environmental assessments differs from the meaning employed here by, for example, including the decision-making process in which environmental assessments could serve as input. The Council Directive 2001/42/EC defines environmental assessment as the "preparation of an environmental report, the carrying out of consultations, the taking into account of the environmental report and the results of the consultations in decision-making and the provision of information on the decision in accordance with Articles 4 to 9" (The European Parliament and the Council, 2001, Article 2, p. 8).

<sup>3</sup> The term environmental pressure will be subsequently used according to the DPSIR (Driver-Pressure-State-Impact-Response) assessment framework used by the European Environment Agency (cf. EEA, 2001). An example of environmental pressure is emissions of carbon dioxide, while the potential damages of climate change to the environment are classified as impacts.

- Paper I “Missing the target? Implementation of industrial ecology in the Swedish transportation sector”. The aim of this paper was to analyse the environmental implications of goals and implemented measures of the implementation process of SIE in the Swedish transportation sector. The paper’s role in this thesis is to exemplify reuse and SIE as used by Swedish authorities.
- Paper II “Environmental evaluation of reuse of by-products as road construction materials in Sweden”. The aim of the paper was to analyse the different possible outcomes of environmental evaluation depending on what system boundaries were applied. Another aim was to examine to what extent the studied tools and methods address resources and pollution aspects, respectively.
- Paper III “Environmental relevance and use of energy indicators in environmental management and research”. The aim of this paper was to investigate the environmental relevance of the energy indicator and discuss implications for its use in environmental management and research.
- Paper IV “Prioritizing building materials in environmental assessment of the Swedish building sector”. The aim of this paper was to point out the most significant building materials that should be focused on in environmental assessments of the building sector, in environmental-related building research and also in environmental management for the building sector.
- Paper V “Environmental analysis of reuse of cast-in-situ concrete in the building sector”. The aim of this paper was to compare the environmental performance of reuse of concrete in relation to construction using only virgin cast-in-situ concrete.
- Paper VI “Recirculation, upgrading and cascading of building materials. What is the difference?” The aim of this paper was to compare different reuse measures of building materials from an environmental perspective.

## Scope of the thesis

This section presents the point of departure for the research included in this thesis. It also concerns the choice of study objects, terminology, as well as some aspects of environmental assessments.

### *The study objects*

This thesis deals with reuse in the building and transportation sectors, since they have had a central role in the implementation of societal industrial ecology in Sweden, due to their role as managers of large material stocks and also users of large volumes of construction materials. These systems stock large amounts of rather homogenous materials. Construction materials mainly contribute to environmental pressures because of the large amounts used in society and the additional processes of extraction, refinement, transportation and also energy use in all life cycle phases.

Construction materials in this context refer to materials that are used in large volumes, i.e. bulk materials, for construction of rail and road infrastructure but also in buildings. The construction materials accumulated in construction sector stock was estimated for 1996 in Sweden to be, in decreasing order: concrete, stones and gravel, bricks and other ceramics, wood materials, lightweight concrete and steel (AB Jacobson & Widmark, 1996). These construction materials were mainly produced from virgin raw materials. A small part of the total amount of construction materials is currently reused materials or industrial by-products. Industrial by-products represent material losses, sometimes as complex compounds of materials that, in contrast to dissipative losses, can be collected. This material category is often mentioned in the reuse context and is, together with reused materials, often referred to as materials that can substitute for virgin resources in the bulk material flows. The virgin bulk materials used in the building and transportation sectors are mainly nonrenewable, except for wood materials. There is also a special case concerning the virgin materials natural gravel and crushed rock, both used for concrete production and also as aggregates in road and rail structures. Natural gravel is an important component in the natural cleaning of ground water used for drinking water. Therefore, an interim target in furtherance of the Swedish national environmental objective "A good built environment" is to minimise the use of natural gravel and instead use crushed rock and reused materials.

### *Terminology for energy indicators and reuse*

Energy use has been included in material balance approaches in order to illustrate that energy always accompanies material use and together these measures complement each other concerning environmental pressure, such as in the embodied energy or exergy concepts (cf. Kloft and Wörner, 1999; Thormark, 2000b; Gao et al., 2001; Johnstone, 2001a; Johnstone, 2001b; Thormark, 2001a; Korhonen, 2002; Sundin et al., 2002; McEvoy et al., 2004). Embodied energy is an aggregated measure of all direct and indirect energy, including materials, that is invested in a product's or material's life cycle from cradle to factory gate (Fay et al., 2000). Embodied energy is based on accounting for primary energy, which is the form of energy extracted directly from nature (ibid.). Electricity is defined as secondary energy since it is produced from primary energy sources such as fossil fuels. Further, the exergy concept is based on thermodynamics and is often explained to be the useful or available part of energy. Exergy is defined as "the potential work that can be extracted from a system by reversible processes as the system equilibrates with its surroundings", (Ayres et al., 1998, p. 192). Exergy is, argued by Ayres et al. (1998) to be "a more natural choice for a common measure of resource quantity than either mass or energy" (Ayres et al., 1998, p. 355). In contrast this, the research in this thesis applied embodied energy and primary energy to study reuse of construction materials. The reasons were mainly that data on embodied coefficients was easily accessible for construction materials and often employed in environmental assessments in building research (cf. Alcorn and Baird, 1996; Alcorn, 1998; Crowther, 1999; Harris, 1999; Fay et al., 2000; Thormark, 2001a; Scheuer et al., 2003; Venkatarama Reddy and Jagadish, 2003). Consequently, studies of reuse of building materials employ energy use as an indicator for environmental pressure (cf. Brown and Herendeen, 1996; Thormark, 2000b; Gao et al., 2001; Klang et al., 2003; Venkatarama Reddy and Jagadish, 2003).

There is a vast array of terms for reuse. The terminology chosen in this research was based on energy-related terms. It was presented by Connelly & Koshland (1997), who organised reuse measures according to their impact on and the degradation of the inner material structure based on arguments on exergy removal (cf. Connelly and Koshland, 1997). The term reuse is thus used as the overall term for any reuse activity. It was divided into recirculation, upgrading and cascading, presented in increasing order of degradation of material quality (ibid.):

- i. “Recirculation” was the term for direct reuse when the inner material structure is not mainly affected, for example direct reuse of building components such as doors and windows.
- ii. “Upgrading” refers to the addition of energy required to bring the inner material structure back to a pre-consumed state. Upgrading was divided into recycling and partial recycling, where partial recycling represents a material structure that does not fully correspond to a pre-consumed state. Examples of upgrading are metal recycling and partial recycling of steel and aluminium products.
- iii. “Cascading” is the term for reuse of a material or product in a degraded form of inner material quality compared to the pre-consumed state, for example, concrete crushed and cascaded into aggregates in road structures.

The reuse projects studied in this thesis were then selected to be suitable for recirculation, upgrading and cascading.

#### *Context of environmental assessments of reuse of construction materials*

Diverse actors and interests are involved in the process of reuse of construction materials, in performing environmental assessments of reuse of construction materials and the following societal decision-making process, if any. In order to understand the context in which these assessments are performed the actors that could be involved will be exemplified here:

- i. political: strategies for non-hazardous and resource efficient (industrial) material cycles (Swedish Government, 2003b; Swedish Government, 2003a)
- ii. research: researchers from several disciplines, performing and discussing environmental analyses, analysis techniques, assessment methods, environment pressure, environmental impact and more,
- iii. analytical: researchers, institutes and consultants performing often standardised analyses of materials to analyse environmental performance characteristics mainly on the order of a customer, for example, the user of construction materials,
- iv. producers: industries producing construction materials and industrial by-products that has an interest in marketing their products,

- v. users: industries and other organisations making use of construction materials and industrial by-products and thereby have to fulfil legal and customer requirements,
- vi. authorities: the decision-makers involved in the process of development consent concerning road, rail or building construction projects or manufacturing industries that make use of reused construction materials and industrial by-products, and
- vii. the public: individuals and nongovernmental organisations have diverse interests in reuse of construction materials such as efficient use of the societal material and economic resources and anxiousness about the risk of pollution of the nearby environment.

This thesis will mainly concern how to assess environmental performance of reuse of construction materials. The actors involved in these assessments' context represent diverse interests and will act after that. Therefore, the ambition with addressing environmental performance of reuse is to some extent to represent the interests of the environment. This means to make it possible to address environmental aspects in a wide perspective in environmental assessments.

Environmental assessments of reuse could be part of the societal decision-making process. Such a process involves, for example, economical and technical aspects and interests that all should be balanced against each other.

#### *Scope of included studies and simplification*

To review environmental performance of reuse of construction materials, energy use in a life-cycle perspective was one assessment method. Concerning building materials, several authors have highlighted that energy use for production of building materials is only a minor part of a building's total energy use; heating and cooling dominating (for example, Cole and Kernan, 1996; Adalberth, 1999; Scheuer et al., 2003). Consequently, it is often argued that reuse of building materials are not that interesting from an energy use and thereby environmental perspective. Nevertheless, reuse of building materials and other construction materials are the focus of this thesis because reuse occurs in society and is believed to contribute to decreased environmental pressure. The building materials' minor part of the environmental pressure of the total energy use in the building life cycle

could also increase when heating and cooling of buildings will be more energy efficient or if the energy sources are changed from fossil based to renewable (Thormark, 2002). Further, buildings are constructed for a total service life of about 50-100 years (Swedish Board of Housing Building and Planning, 1998). Additionally, environmental assessments of buildings often address a service life of about 50 years. If these constructions instead are demolished after 20-40 years, which is sometimes the case in Sweden, the invested energy for producing these buildings is distributed over a shorter time period. This contributes to an increase in the share of the total energy use of the building materials. Similarly, the study of cascading of materials into road structures (in Paper VI) used an analogous arguing for leaving out the operation phase of the road. This procedure is also applied by, for example, McEvoy et al. (2004) who used a mass balance approach including energy use in order to calculate environmental pressure of construction minerals such as limestone, sandstone, granite and building stone, through their life cycle.

Organisations commonly use simplification of reality into a set of few indicators to follow its progress and development of measures and strategies (see for example Smeets and Weterings, 1999); as well financial as operational and now days also environmental. A popular *truth* is “what you measure is what you get” (Kaplan and Norton, 1992, p.71)), which implies that measurements and indicators become important for proactive environmental management. Moreover, there is need to balance between prioritised areas (ibid.) because one single indicator could not provide a clear message of the entire organisation strategies and objectives. In contrast, too many indicators in several areas would be too much workload; hard to interpret all together and thereby also difficult to communicate. A parallel can be drawn to environmental related indicators that could be large sets of indicators, for example, used in life-cycle assessments (LCA) and environmental management systems (EMS) or single indicators such as emissions of carbon dioxides or primary energy use applied in screening processes or simplified environmental analyses. However, few indicators can never fully describe the complex reality of environmental problems and there is always the risk of problem shifting. Problem shifting represents the situation when measures to prevent environmental problems give rise to negative environmental pressures in another space or time or lead to other environmental pressures (Raadschelders et al., 2003). Therefore it becomes important to

find a balance between avoiding problem shifting and using simplified methods and few indicators.

Side-effects and problem shifting is always a risk in scoping<sup>4</sup> environmental assessments and environmental management, especially since the nature of environmental problems is very complex. Since studies using narrow system boundaries lead to detailed information about well-defined issues and studies applying wide system boundaries provide comprehensive information about larger systems, applying only one of these seem to increase the risk of side-effects and problem shifting. In order to cope with several perspectives various environmental assessments with different system boundaries would be performed (cf. John and Zordan, 2001). This thesis analyse environmental performance applying different system boundaries and assessment methods.

#### *Summing up scope of the thesis*

The studies performed in Paper I-VI have had a primary interest in assessing environmental performance of the reuse of construction materials that actually was performed and not the potential environmental benefits. The data used were mainly project-specific and exemplify some current reuse practice in Sweden rather than being general. Further, it seems that there could be a lack of simplified and simultaneously environmental relevant

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<sup>4</sup> Scoping as used in the context of environmental impact assessments is the process of identifying environmental pressure as well as the people the project and its potential environmental pressure will affect (Jones, 1999). Moreover, the values held by different interests could also be included in the scoping process after public participation. Not until then it can be decided on what to emphasise, what system boundaries to apply and what methods to use for further environmental assessment of the project (ibid.). Even though this scoping process originates from the context of environmental impact assessments it is principally utilised in one form or another before any performing of environmental assessments.

assessment tools for environmental performance of reuse. The approach in this thesis was mainly a synthesis of parts of several research areas, such as environmental assessment methods, reuse of building materials, environmental policy and decision-making and do not very deeply consider the parts that have contributed to it. This research was thus intended to contribute to a broader perspective on reuse of construction materials and how to environmentally assess it.

## Theoretical framework

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This presentation of a theoretical framework aims at a continued and deeper discussion of the introductory part of the thesis.

### Environmental assessments with a systems approach

The term environmental assessment, in this context, is used as a general term for any kind of environmental analysis, evaluation or assessment, including the process of analysis and interpretation of the results. This means, for example, that performing laboratory tests without trying to interpret what they mean for the environment is not classified as an environmental assessment in this thesis.

Environmental assessments could be performed using several methods or tools and concepts. Udo de Haes et al. (2000) stated that the term tool should be kept apart from the term concept, which relates to general principles, such as Industrial Ecology, and Baumann and Cowell (1999) reserved the term concept, used for environmental management, for an idea to achieve sustainability. The latter authors also defined tools as “an approach that typically consists of a systematic step-by-step procedure and a mathematical model” (Baumann and Cowell, 1999, p. 111). Furthermore, Udo de Haas et al. (2000) divided tools into analytical tools and procedural tools. The analytical tools were described as principally consisting of mathematical models and correspond to the term tool as defined by Baumann and Cowell (1999). Examples of analytical tools include material flow accounting (MFA) and life-cycle assessment (LCA). Procedural tools were defined as those that consisted of prescriptions and guidelines regarding responsibilities and also process steps to be taken. Examples of procedural tools are environmental management systems (EMS) and strategic environmental assessments (SEA). Usually, the terms methods and tools are used for the same purpose and there is no distinction between these. However, as I interpret these terms, tools are methods based on quantitative data, i.e. analytical tools as Udo de Haes et al. (2000) describe them, while methods would include both qualitative and quantitative information, i.e. both analytical and procedural tools.

A systems approach deals with a large variety of problems and is applied in many different contexts, not merely in the environmental field. Environ-

mental assessments should reach some significant characteristics in order to be classified as applying a system approach. Some examples, after Miser and Quade (1995), are that the assessment *context* would originate in complex problems including interactions with society and the environment. The *method* used would be a synthesis of, for instance, understanding, analysis, design, intuition and a scientific approach. Further, the *tools* would, for example, be logic, statistics, technology or multi-disciplinary. The *aim* of an assessment would be to seek improvements by, for example, evaluations. The *clients* would be those who have an interest in the improvement and there would be a continuous interaction between them and the analysis team characterising their *relation*. The studies performed in this thesis were as long as possible trying to reach these characteristics: the context of the environmental assessment was complex, as described earlier; the method was to build knowledge on understanding the context, method development and to perform environmental assessments with a life-cycle approach. The overall aim was to contribute to a good basis for environmental assessments that in turn could lead to improved environmental performance.

Early studies in industrial metabolism emphasised small but toxic material flows such as lead, mercury and cadmium in well-defined geographic areas using mass balances with such analytical tools as material or substance flow analysis (MFA or SFA) (cf. Ayres and Rod, 1986; Tarr and Ayres, 1987; Anderberg and Stigliani, 1994). Lately, material flows of large volume materials for entire nations have been calculated using tools such as MIPS (Material Impact Per Service) or TMR (Total Material Requirement) (cf. Bringezu and Schütz, 2001). More specifically, industrial metabolism is a theoretical systems approach or perspective that considers material and energy flows in the technosphere as the key aspects to study in order to prevent and predict environmental problems (cf. Anderberg et al., 1989; Ayres, 1994; Fischer-Kowalski, 1998). The holistic approach of industrial metabolism contributes to preventing sub-optimisation and side effects of measures taken. The material inflows, such as use of natural resources and energy, as well as the material outflows, such as emissions of metals and carbon dioxides (CO<sub>2</sub>) into air, soil and waters all contribute to environmental pressure. However, traditional end-of-pipe technologies mainly focusing on the material outflows could not cut off the source to environmental impact and could therefore contribute to a sub-optimisation of environmental measures and problem shifting (Raadschelders et al., 2003). To keep track of the material stock, i.e. the accumulation of materials in soci-

ety helps to foresee future environmental pressures, due to the thermodynamic laws of “what comes in comes out”, even though there could be a time delay. Therefore, mass balances that simultaneously consider material inflows, outflows and also the material stock from a systems perspective make it possible to address both present and future environmental pressure (cf. Anderberg et al., 1989; Bergbäck et al., 1992; Ayres, 1994; Brunner et al., 1994).

Industrial ecology takes its foundation from industrial metabolism, which is the theoretical basis of this research, i.e. the overall approach including choice of research questions, study objectives and methodologies. Industrial metabolism focuses on understanding environmental problems through thermodynamics (Ayres, 1994). The thermodynamic laws state the principle of conservation of energy and matter and that the entropy in closed systems is likely to increase (Kittel and Kroemer, 1980). Energy as well as matter will not disappear, only convert into other forms. For example, during the use of materials and energy there are environmental interactions that lead to dissipative losses of material and energy. This increase in entropy can be described as a loss of quality in the converted energy or matter. The quality loss is manifested as a decreased order in the structure of matter or the form of energy. To regain quality, i.e., to convert matter or energy to a more structured form, a process that decreases entropy (locally) must be applied. The consequence for reuse is need for energy and new virgin material to be added into reuse processes in order to dilute the impurities and to regain higher material quality. More and more energy has to be added to each reuse cycle in order to bring the material or product back to its pre-consumed state (cf. Connelly and Koshland, 1997).

It might be productive to apply wide scope or system boundaries to environmental assessments of reuse of construction materials (cf. Inyang et al., 2003), which could lead to more complex assessment methods. Several analytical and also qualitative tools or procedural tools could be used during the process of performing SEA (Finnveden et al., 2003). Since SEA is designed to deal with complex societal changes, it could be a relevant process for assessing reuse of construction materials. On the other hand, if assessment methods are to come into use in society they should be easy to understand and accomplish, which seems to depend on the context in which the method or tool is used (Lindahl, Manuscript). However, any use of a method, for example an environmental assessment method, involves simplification of the complex relations between society and environment; that

is, the reduction of complex problems into models that could be addressed. Further, complex assessment methods could be very time-consuming and if an analysis requires too much data or if the data cannot be interpreted Hertwich et al. (1997) suggest that there is a risk for “analytical paralysis”. This means that the work could decelerate or produce a poorly expressed outcome. Therefore, an ambition in this research was to develop methods that can manage a balance between simplification and a wide scope in environmental assessments.

### The Swedish concept of *kretsloppsanpassning* and industrial ecology

The Swedish government released in 1993 a strategy to resource-saving materials and energy use in order to achieve the ultimate goal of ecologically sustainable development (Swedish Government, 1993). The concept launched was termed *kretsloppsanpassning*<sup>5</sup> and it has structural similarities to the concept of industrial ecology. Industrial ecology is an emerging concept within the academic world dealing with how to describe and analyse industrial systems and their interactions with the biosphere (O'Rourke et al., 1996; Erkman, 1997). It also includes how to improve industrial systems and sometimes how to make them imitate natural ecosystems. The analogues of industrial ecology and this Swedish concept concern both the overall objectives and the strategies for implementation. Examples of parallels are that both concepts have ecologically sustainable development as an ultimate goal and that one central strategy is to close the material cycles (Swedish Government, 1993; Erkman, 1997). The society that the Swedish government envisioned in 1993 and in the later Government Bill 2002/03:117 would have a good natural resource economy and would stimulate reuse of materials and minimise the total environmental impact from materials and products (Swedish Government, 1993; Swedish Government, 2003b; Swedish Government, 2003a). This ideal materials management would, according to the Swedish government, lead to mini-

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<sup>5</sup> The Swedish word *kretsloppsanpassning* consists of the words *kretslopp* and *anpassning*. *Kretslopp* originates from the science of ecology and means a cycle or a flow of substances or energy. The word *anpassning* is, translated to English, adaptation. In Sweden a common translation of *kretsloppsanpassning* is “ecocycling”, as for example in the Ecocycle Council for the Building Sector (Byggsektorns kretsloppsråd) and also The Ecocycle Commission (Kretsloppsdelegationen). However, I find “ecocycle” and “ecocycling” misleading, since they associate so much to ecology, while *kretsloppsanpassning* is something that concerns all material flows of the entire society.

mised generation of wastes and minimised contribution of emissions to the environment. Another strategy, present in the Swedish concept as well as in industrial ecology, is the shift from the utilisation of nonrenewable natural resources to renewable ones. Both concepts emphasise how industrial material and energy flows should imitate nature in its way of closing the material cycles and minimising the use of resources (Swedish Government, 1993; Erkman, 1997). Since natural ecosystems constitute a norm for both industrial ecology and the Swedish concept, this implies a normative nature of their implementation (for industrial ecology see (Boons and Roome, 2001)). As the Swedish concept *kretsloppsanpassning* is very close to industrial ecology yet should be implemented throughout society, the term societal industrial ecology (SIE) could be a proper English term.

Since the ambition was to implement SIE in all societal sectors, such as agriculture and forestry; transport; energy supply; industry; physical planning and solid waste and wastewater management, the Swedish National Rail Administration and the Swedish National Road Administration were commissioned by the Swedish government to implement the concept. The government directives addressed the infrastructure's life cycles as well as activities that take place during the construction phase and management (Swedish National Rail Administration, 1996; Swedish National Road Administration, 1996). Examples of goals addressed in these Administration action plans were reduced use of non-renewable natural resources, reduced dispersion of pollutants and use of hazardous materials and increased reuse.

A measure the Swedish government used for implementation of SIE was the introduction of the producer's responsibility that encompassed the responsibility to handle the future waste from products. This responsibility was firstly directed to actors such as the packaging industry and the building sector. However, the building sector was not legally bound to this responsibility; it was and still is a voluntary agreement (Swedish Government, 1993; Swedish Government, 2003b; Swedish Government, 2003a). The building sector has developed an environmental programme where four comprehensive goals were addressed (The Ecocycle Council for the Swedish Building Sector, 2003): i) minimising energy use in buildings, ii) minimising building waste, iii) phasing out environmentally hazardous substances, and iv) guaranteeing a good indoor environment.

The present role of societal industrial ecology in the Swedish environmental politics is as one of 15 emphasised areas (Ministry of Sustainable

Development, 2005a) and also one of three guiding strategies in the work to reach the environmental objectives (Ministry of Sustainable Development, 2005b).

### Reuse of construction materials in Sweden

Reuse of construction materials in Sweden has so far been a small business for most material categories. The exception concerns the bulk material flow of different stones and gravel, estimated to represent more than 50% of the total amount of the accumulated construction materials in the Swedish technosphere and more than 70% of the yearly produced construction and demolition wastes in Sweden (AB Jacobson & Widmark, 1996). About 90% by weight of the produced waste of stone and gravel were estimated to be recirculated in 1996. The uncertainty in these figures was estimated to be  $\pm 20\text{-}40\%$ . Reuse data on many of the material categories were lacking in the study.

There are second-hand markets of used construction materials from buildings for minor building projects, see for example [www.byggigen.se](http://www.byggigen.se). There are only a few examples of multi-family dwellings or other larger constructions that to a large extent are built using used building materials, at least in their frame structure. It is more common to cascade a demolished building, after selective demolition, into filling materials for landscaping in the immediate surroundings or into smaller roads or paths. To some extent, different by-products from industry are also used for the same purpose. Since roads and railways have a long service life and the demand for transportation is still increasing, the outflow of structural materials from roads and rails is low on a yearly basis. However, asphalt from road pavement is often reused in the new pavement on site or elsewhere. Regarding metals, they are commonly upgraded or cascaded in the metal industry because of their economic value. Wood materials are commonly used as bio-fuel in combustion power plants.

Conditions and constraints for reuse in Sweden have been researched by Thormark (1997) and Eklund et al. (2003). Eklund et al. (2003) concluded that important constraints were financial and lack of practice, however, techniques were expected to be developed when needed. Other constraints on large-scale reuse are how to test quality, how to store the deconstructed materials and how to find available materials for reuse (Thormark, 1997).

Reuse of construction materials is considered in societal industrial ecology because of their nonrenewable characteristics and because closing material cycles is a basic principle (Swedish Government, 1993; Swedish Government, 2003b). This has also led to addressing increased reuse as a goal in implementing SIE, as the reuse would be a measure for resource-saving material and energy use.



## Methodology

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This section of the thesis will present the overall research methodology and the methods used in the papers.

### The research process and the papers

Starting PhD studies with a broad research area such as "environmental perspective on management of infrastructure" rather than a well-defined research project, the research process led me into unpredictable ways and issues. The learning process led to new knowledge and findings from which new questions were raised and new studies developed. Interaction with other societal actors, such as industries, authorities and other researchers, also contributed to the learning process by injection of new perspectives and inspiration. Therefore, this development of research issues that were continually raised from the findings of an earlier study should be seen as a part of the methodology. This process and the methodology used in the papers are described here.

One overarching ambition was to study environmental performance of reuse. However, since this research area is still under development and lacks the characteristics of an established traditional discipline such as well-adapted methods, method development had to be addressed.

In the beginning of the research process three individual studies were performed. Firstly, the stocks and flows of environmental hazardous materials in the road environment were addressed (see Roth and Eklund, 1999). This study applied the material flow perspective and was performed in order to try the approach of substance flow accounting (SFA) of a motorway environment instead of traditional SFA spatial boundaries, such as nations, islands or river basins. The project also led me into the use of industrial by-products in road construction. Secondly, an environmental analysis of reuse of cast-in-situ concrete was performed (see Paper V). The study applied a simplified version of life-cycle assessment: life-cycle accounting of used concrete compared to virgin materials. Further, the environmental management concerning material and energy use in the implementation of societal industrial ecology in the Swedish Rail and Road Administrations, respectively, was studied (see Roth and Eklund, 2000 and Paper I). This was also a study of concepts and goal definitions in the implementation of

societal industrial ecology. Methodologically, it was based in industrial metabolism and considered material and energy inflows, outflows and stock. Summarising this research in a licentiate thesis (see Roth, 2001) led to a development of a framework for the environmental assessment of reuse of industrial by-products (Paper II), which was the result of the learning process and the earlier studies performed.

These initial studies also nurtured an interest in environmental differences between various reuse measures, which was addressed in Paper VI, where recirculation, upgrading and cascading of building materials was examined in terms of their energy use in a life-cycle perspective. However, in order to be able to perform research for Paper VI, research to examine and understand the use of energy as an indicator for environmental pressure (Paper III) and research to point out the most important building materials to focus on (Paper IV) had to be accomplished. The task in Paper III was approached from environmental impact categories specified in life-cycle assessment (LCA) literature. The critical review of energy use as an indicator for environmental pressure was based on accounting, or qualitative arguments if figures were not available, of the energy use's share of the total environmental pressure from each impact category. The final characterisation of the indicator's possibility to reflect environmental pressure was an interpretation of these results. Further, the prioritising of building materials in Paper IV was methodologically based on an accounting of the embodied energy, normalized for service life, in the Swedish building material stock.

To sum up, as the aim of this thesis was to examine under which conditions reuse of construction materials could be beneficial to the environment (presented in Papers I, V, VI), it was necessary to develop or adapt environmental assessment methods required for this research task. In order to facilitate the environmental assessment of reuse of construction materials a framework was developed (see Paper II). Also, simplified indicators and screening tools to point out the research focus were needed (see Papers III-IV).

### Missing the target? Implementation of industrial ecology in the Swedish transportation sector (Paper I)

Since societal industrial ecology (SIE) emphasises resource-saving materials and energy flows and closing the material cycles, it was considered relevant to review the implementation of SIE through material flows, in-

cluding reuse, in a life-cycle perspective. Further, the commission from the Swedish National Rail and Road administrations, respectively, concerned an implementation of SIE in all life cycle phases. It was assumed that what was reported in the annual environmental reports also shows what issues were prioritised in their environmental management. Consequently, to some extent this pointed out what the authorities considered to be significant environmental performance. Therefore, the methodology was to review the material and energy inflows, outflows and stock in the environmental reports and categorise them into the life cycle phases of construction, management, use phase and end-of-life. The actual measures described in the environmental reports were categorised with regard to which life cycle phase they involve.

#### Environmental evaluation of reuse of by-products as road construction materials in Sweden (Paper II)

The development of a framework for the environmental assessment of reuse of by-products as road construction materials was based on a comparison of environmental assessment methods. These were discussed according to system boundaries and which environmental issues the methods could address. The system boundaries were organised into four system levels from narrow to wide system boundaries: the material level, the road environment level, the narrow life-cycle level and the industrial system level. These system levels and their possible assessment methods were especially examined for their capability to address pollution and resources aspects, as these both are relevant environmental aspects for reuse in general, as well as for the SIE concept.

#### Environmental relevance and use of energy indicators in environmental management and research (Paper III)

The ambition to employ simplified environmental methods that illustrate relevant environmental pressures was the motive when performing this review of energy use as an indicator for environmental pressure. The method was a combination of how the European Union (EU) energy use was distributed over the Households & Services, Industry and Transportation sectors, and additionally the characterisation of environmental pressure from energy use into the environmental impact categories often used in LCA (cf. Guinée, 2001). In order to approach this complex issue, a reductionist perspective was used, which means that the system boundaries were narrowed

and each environmental impact category was more or less assessed individually and in isolation from other factors affecting it. The accounting procedure was based on the societal sectors' share of energy-related environmental pressure from energy use contributing to the total picture of the EU as a whole. However, the estimated levels of an energy indicator's ability to reflect different impact categories could not be described in quantitative terms only and thus qualitative aspects such as the scale and the character of the expected environmental pressure were included in the final assessment.

### Prioritizing building materials in environmental assessment of the Swedish building sector (Paper IV)

Paper III describes which environmental pressures an energy indicator could reflect. This indicator became a significant part in the development of a prioritising procedure of building materials. Concerning energy and material resources, an approach to assess the building sector's most important materials could be based on either the embodied energy coefficients for each material category or the quantity of materials in the building stock, or both, which then could represent the embodied energy in the building material stock. However, since building products and materials have diverse service lives, the ranking has to be normalized by the time the products could be estimated to be in use. The resulting environmental pressure indicator gives an indication of the amount of energy invested in the stock of diverse materials. The ranking could point out which building material categories were the most significant from a material and energy resources perspective and therefore would be interesting to reuse.

### Environmental analysis of reuse of cast-in-situ concrete in the building sector (Paper V)

The method in this paper followed a narrow scope of LCA with a retrospective perspective, also called accounting LCA, in contrast to the prospective perspective of LCA that models effects of changes (cf. Tillman, 2000). This narrow scope of LCA, sometimes termed streamlined LCA (cf. Todd and Curran, 1999) or simplified LCA, follows the overall procedure for a "full-scale" LCA, but by deliberate choice excludes or simplifies what is included in the study. This methodology was applied in order to assess the environmental performance of recirculation of cast-in-situ concrete compared to the use of virgin materials for a few key environmental as-

pects. These were assumed to be related to transportation activities, which is why primary energy use and emissions of nitrogen oxides (NO<sub>x</sub>) were chosen as parameters in the inventory. Additionally, carbon dioxide (CO<sub>2</sub>) emissions were calculated for the studied life cycle. The accounting neither considered earlier environmental pressure caused by the recirculated cast-in-situ concrete nor the processes avoided by the recirculation.

### *The case study*

The case studied was a pilot project where cast-in-situ concrete from a building constructed in 1960 was sawn into elements and then moved by long-distance trucks 64 km to be recirculated as prefabricated concrete in a new concrete frame structure. The total amount of recirculated concrete was 360 tonnes (Linköpings universitet avd för Industriell miljöteknik et al., 1999). In order to meet the present building norms it was necessary to insulate the inner walls. This was done by using 26 tonnes cast-in-situ concrete for the slabs, almost 4 tonnes angle iron, almost 8 tonnes gypsum boards and almost 1 tonne mineral wool and wood studs (ibid.). The new building had a foundation of concrete produced from virgin raw materials.

### Recirculation, upgrading and cascading of building materials. What is the difference? (Paper VI)

In order to compare recirculation, upgrading and cascading, a life-cycle accounting approach to energy use was applied to the reuse of concrete and clay bricks. A similar streamlined life-cycle approach to that in Paper V was used; however, the system boundaries were widened in scope with regards to the processes included. Energy use was employed as an indicator for environmental pressure as it was found to be environmentally relevant for processes occurring in fossil-based energy systems and for nontoxic products (cf. Paper III). The studied materials were those building-sector-specific materials that ranked the highest from the perspective of embodied energy in the Swedish building material stock (Paper IV), excluding wood materials that mainly are combusted in power plants. In order to illustrate current reuse in Sweden, this study used data from actual reuse building projects. Consequently, it consists of realistic examples of current reuse.

To be able to compare reuse measures in a life-cycle perspective, the reuse activities were credited for processes that were avoided. Firstly, calculations on primary energy use were performed for each reuse measure and for

a comparative case using virgin materials. Secondly, with the aim of illustrating the environmental differences between recirculation, upgrading and cascading, the reuse cases were credited for avoided processes such as the new production of virgin materials and transportation to landfill. The functional unit for each reuse alternative was 1 tonne of the final product.

### *The studied cases - concrete*

One of the concrete reuse cases studied involved recirculation of two multi-family dwellings of cast-in-situ concrete sawn into building elements, transported by truck to the new building site, 64 km away, and reused in a new, completely different multi-family dwelling (see the front cover of this thesis for an illustration of the deconstruction and the back cover with a detail from the new building). The total amount of reused concrete was 360 tonnes (Linköpings universitet avd för Industriell miljöteknik et al., 1999). The new building had a foundation of concrete slab produced from virgin raw materials. Inner walls were insulated to meet current building norms by using 26 tonnes of cast-in-situ concrete for the slabs, almost 4 tonnes of angle iron, almost 8 tonnes of gypsum boards and almost 1 tonne of mineral wool and wood studs (ibid.). The reference case was assumed to be constructed of cast-in-situ concrete.

Recirculation of prefabricated concrete was studied through deconstruction of multi-family dwellings. The elements were stored, transported (total distance 64 km, one way) and rebuilt like the original construction, but smaller. The total amount of recirculated concrete elements was 1850 tons. The new building had a concrete foundation produced from virgin raw materials. In order to meet newer building norms, the construction had to be complemented with 75 tonnes of gypsum boards, 30 tonnes of sheet and forge iron and 7 tonnes of stone wool (Fredriksson, Sundbaum Bygg & Miljö, pers. comm.). The reference case was an equivalent building produced from virgin materials actually constructed: 1555 tonnes of prefabricated concrete were used (ibid.).

In the case of upgrading concrete it was assumed that it was crushed into aggregates for use in the production process of new cast-in-situ concrete, which was then used for a similar multi-family building described above. In total, 20% (cf. Hendriks et al., 2000) of the aggregates produced from virgin materials was assumed to be substituted with crushed concrete. The

reference case was assumed to be a cast-in-situ concrete building produced from virgin raw materials.

The final case involving concrete was the demolishing of a building by crane, crushing in a mobile impact crusher and then, after sorting, cascading as aggregates in a road structure. Since road structures could vary widely in construction, depending on the geological ground conditions, the calculations only included crushing of materials, deconstruction of the old building, and transportation to the road construction site. About 50% of the used road construction materials was assumed to be crushed concrete (cf. Arm, 2000). A reasonable transport distance for these materials is 20 km according to Mroueh et al. (2001). The reference case was assumed to be crushed rocks, transported 35 km (Starkenber, BEFAB Konsult AB, pers. comm.) to the road construction site.

#### *The studied cases - clay bricks*

The first clay brick reuse case involved the recirculation of clay bricks from an old hospital building into a residential building. The old building was selectively demolished and the masonry structure was manually deconstructed and cleansed, brick by brick (Sternudd and Swensson, 1997; Thormark, 2000a). The bricks were stored and later transported to the new building site, 17 km away. Manual deconstruction and cleansing of the bricks was assumed to lead to material losses of around 25% (ibid.). The new construction with reused building materials had to use extra materials such as 5 tonnes of virgin wood studs, 5 tonnes of reused wood studs and 1 tonne of new steel, while the reference case of virgin materials required 8 tonnes of wood studs but no steel (Thormark, 2000a). The total amount of reused clay bricks was 90 tonnes, compared to 80 tonnes new clay bricks in the reference case (ibid.).

The removal of mortar from the clay bricks could also be done by re-burning the bricks in a tunnel kiln at an ordinary brickworks (Kristensen, 1993). The re-burning processes utilise large amounts of energy and affect the inner material structure. Consequently, reuse with re-burning will be classified as upgrading. The bricks would be hard-burned after the re-burning and are manually cleansed in much less time. The building project studied for upgrading was assumed to be the same as for recirculation, with the exception that the clay bricks were re-burned instead of manually cleansed and that the demolition was done with a digging machine, which is easier

and quicker than manual deconstruction, but generated material losses of about 40%. Thus, the reference case was the same as in the case of recirculation.

Reuse through cascading was in this study exemplified by crushed masonry (both the clay bricks and the mortar) being reused as aggregates in concrete production. The studied case was assumed to use 10% crushed masonry (Hendriks et al., 2000) in a cast-in-situ concrete building. The transportation distance from the demolished building to concrete manufacturing was assumed to be 35 km, the same as the maximum distance crushed rocks are transported (Starkenber, BEFAB Konsult AB, pers. comm.). The reference case was the cast-in-situ concrete building produced from virgin materials, as described for recirculation of cast-in-situ concrete.

## Results from the papers

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This section of the thesis is a short overview of the results presented in the papers. For a thorough discussion of the individual results see the respective appended paper.

### Missing the target? Implementation of industrial ecology in the Swedish transportation sector (Paper I)

This study indicates that the general ideas and the goals presented for societal industrial ecology (SIE) were principally preserved when incorporated into the transportation agencies' action plans. However, the further transformation of SIE principles into environmental management performed by the agencies was not entirely consistent with intended aim. Studying the implemented measures, these were mostly restricted to addressing material outflows in the management of infrastructure, in contrast to the governmental ambition of SIE additionally addressing material and energy inflows and the material stock over the entire life cycle.

One outcome of the inventory of the agencies' environmental management was that there appeared to be an unbalance between management of inflows and outflows of energy and materials. The inflows were quantified: for instance, some inflows of construction materials, chemicals for management measures and fuel consumption for traffic were presented in the environmental reports. However, measures were mainly implemented on the outflow side, such as protection of water supply areas from emissions of particles from the road surface and vehicles; improvement of motor engines in working machines; shifting to low-emission fossil fuels in working machines, and increased reuse of materials disposed of in the management phase. It should be noted that flows that were quantified and recorded yearly were not subject to measures. On the other hand, the implemented measures were often not related to the quantified indicators. The stock of materials in the infrastructure is poorly considered overall in the environmental management that is accounted for in the environmental reports.

The agencies' environmental management is not governed by a life-cycle perspective, despite the fact that the government directive to implement SIE included such a perspective and that the agencies make occasional use of life-cycle assessments of infrastructure products. This could be observed

in the inventory, as no accounting for material and energy flows in the deconstruction phase was reported, although a few examples refer to the construction phase. Furthermore, the implemented measures are restricted to the management phase.

Nevertheless, increased reuse was one of the goals in the action plan for implementation of SIE in the road infrastructure as well in the SIE ambitions. However, it was not to a large extent reported in the environmental reports. The information found concerned reuse of asphalt pavements in the management phase of the road and also utilisation of by-products from other industrial activities in the road construction. Considering deconstruction of infrastructure, there was no activity reported concerning reuse. Therefore, it was concluded that reuse activities had not had a major breakthrough during the studied period, 1991 to 1999.

#### A framework for environmental assessment (Paper II)

The framework is constructed of four assessment levels or system levels addressing different system boundaries. The narrowest level is termed the *material level*, then the *road environment level*, the *narrow life-cycle level*, and the widest is termed the *industrial system level*. These levels address different system boundaries (Figure 1), which to some extent decide which environmental issues can be addressed at each level.

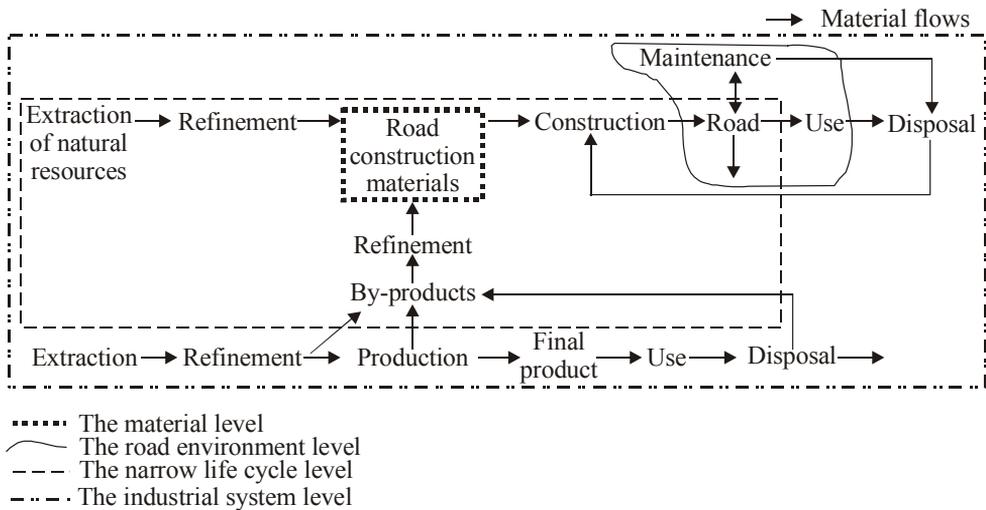


Figure 1. The system boundaries used at the four levels are illustrated by different borders. These encircle the specific parts of the production chain that studies at a certain level could take into account. The widest, the industrial system level, includes all the others. Studies performed at this level could address environmental issues in a very broad sense, perhaps not very deeply. The system boundaries on the narrow life-cycle level and the road environment level, respectively, overlap each other. Most of the current environmental evaluations of reuse of by-products deal with the material level and thereby contribute knowledge needed at all other levels.

From the system boundaries and addressed issues, it follows that different environmental assessment methods or tools are suitable at different levels. For example, the material level addresses issues such as which substances are present in a material and if and how they *could* leach from the material to the environment. Chemical analysis of substances and the material's leaching characteristics could be performed at this system level. A common approach is to compare total and leachable chemical substances with different limits.

The road environment level deals with the environment in which the by-products are intended to be used, the amounts of the studied substances in the by-product and the nearby environment of the road structure. This level could involve studies of the carrying capacity of the road environment and the total flows of a substance in a region. Methods that could be applied at the road environment level are substance or material flow accounting (SFA/MFA) and environmental impact assessment (EIA), with the use of data from the material level.

The next level is the narrow life-cycle level, which widens the scope of the assessment to include environmental pressures upstream and downstream in the materials' life cycle. Possible assessment methods were therefore life-cycle assessment (LCA) and EIA. The term narrow is intended to allow limited system boundaries in terms of studying a restricted part of a life cycle and also a selection of indicators to address environmental pressure. Additionally, the narrow life-cycle level only partly addresses the issue of substitution of virgin raw materials, such as substitution of natural gravel or crushed rock with crushed concrete.

The industrial system level represents a very broad approach and could include studies coping with several issues, perspectives and several actors and their specific interests. The wide system boundaries required at this level include, for example, the issues of which natural resources were substituted by reuse of industrial by-products. Thus, environmental assessment methods and tools that could cope with this industrial system level require further development to fully include all desired aspects. As a start, "full-scale" LCAs and strategic environmental assessments (SEA) could be possible methods or processes.

To sum up, the system boundaries of the material level and the road environment level are the most appropriate for studies of pollution aspects of the reuse of by-products, because they allow for a focus on a local scale (Figure 1; Table 1). On the other hand, studies performed at the narrow life-cycle level and at the industrial system level could additionally include the utilisation of natural resources and thereby address other environmental issues. Nevertheless, the final interpretation of the results from an environmental assessment, at any level, includes the prioritising among the current pressing environmental issues and is therefore contingent upon values.

Table 1. An overview of answers to the questions this article set out to answer.

	<b>The material level</b>	<b>The road environment level</b>	<b>The narrow lifecycle level</b>	<b>The industrial system level</b>
<b>The environmental aspects the tool or method addresses</b>	Total chemical content and leaching behaviour	The by-products in the environment they should be reused in	Key environmental aspects during a part of the life cycle	Overall environmental aspects
<b>Does the method or tool contribute to the study of pollution aspects?</b>	Yes	Yes	Partly	Partly
<b>Does this method or tool contribute to the study of resource aspects?</b>	No	Partly	Yes	Yes
<b>The result of an environmental evaluation</b>	Contingent upon values and dependent on substances studied	Contingent upon values and dependent on substances studied	Contingent upon values and dependent on the selection of parameters, system boundaries and allocation principles	To a large extent contingent upon values and system boundaries

### Environmental relevance and use of energy indicators in environmental management and research (Paper III)

The main point in this paper was to show that an energy indicator reflects different environmental impact categories to different extents. When the environmental pressure generated by the energy system within the European Union is allocated to different environmental impact categories, it becomes obvious that many of the impact categories become affected while others do not (Table 2). In addition, the marks in Table 2 are not to be seen as a ranking of which environmental pressure is most important, since this is contingent upon values.

Table 2. Summary of the energy indicator's estimated reflection of environmental impact categories for the energy system of EU-15. The degree of reflection is estimated as strong (●●), moderate (●) or weak (○). Uncertainty regarding the classification is indicated with two symbols separated by a slash (/). One category is not necessarily comparable with another in terms of environmental pressure, i.e. a moderate reflection in one category may render a larger relative environmental impact than a strong reflection in another. However, the differences between sectors are comparable.

Impact categories	EU-15, Services & Households	EU-15, Industry	EU-15, Transportation	EU-15, TOTAL
Depletion of abiotic resources				
- Fossil fuels	●●	●●	●●	●●
- Minerals	○	○	○	○
- Metals	○	○	○	○
- Renewable abiotic resources	○	○	●	○/●
Depletion of biotic resources	○	○	○	○
Impact of land use	○/●	○/●	○	○/●
Desiccation	○	○	○	○
Climate change	●●	●●	●●	●●
Stratospheric ozone depletion	○	○	○	○
Toxicity aspects				
- Metals	○/●	●	○	○/●
- POPs	○	○	●	○
- Particles	○	●	●●	●/●●
- Hazardous chemical flows	●	○/●	●●	●/●●
Photo-oxidant formation	○/●	○/●	●●	●●
Acidification	●	●	●	●
Eutrophication				
- marine waters, nitrogen	○	○	●	●
- inland waters, phosphorus	○	○	○	○
Waste heat	●●	●●	○	●●
Odour	○	○	○	○
Noise	○	○	○	○
Impacts of ionizing radiation	○/●	○/●	○	○/●
Casualties	○	○	○	○

The Services & Households sector consists of many actors, meaning that to some extent the environmental pressures depend on the activities of individual actors. However, the strongest reflection between the energy indicator and environmental pressure occurs for the categories of depletion of

fossil fuels, climate change and waste heat (Table 2). This pattern is the same for the Industry sector. Furthermore, there are other important environmental pressures from Industry that are not directly energy related, for instance use of chemicals, which is not highlighted in Table 2. This also applies to environmental assessments of products and services: The energy use indicator can reflect toxic effects that depend on energy production while it will not say anything about the toxic effect contributed by the product itself. Considering the Transportation sector, emissions from vehicles are mainly uncontrolled and the handling of petroleum products is rather dangerous, which suggests that the energy indicator gives a strong reflection of depletion of fossil fuels, climate change, photo-oxidant formation and toxicity aspects of particles and hazardous chemicals (Table 2).

Energy use is a particularly relevant indicator in environmental management of and research in the building and construction, transportation and energy sectors. However, when the energy indicator is used as a single indicator, the aim and context in which it is used must be apparent in order to enable the correspondence to some basic requirements, such as: i) the energy system it is applied to, ii) a reflection of the overall environmental characteristics not covered by energy use and iii) the need for the description of the energy indicator to be transparent to the receiver.

#### Prioritising building materials (Paper IV)

This paper intended to point out which building materials to prioritise for reuse projects (presented in Paper VI). It originated in prioritising the materials according to their embodied energy coefficients (Figure 2a) and a mass-based indicator, which organises the materials according to their share of the accumulated amount in the total building material stock (Figure 2b).

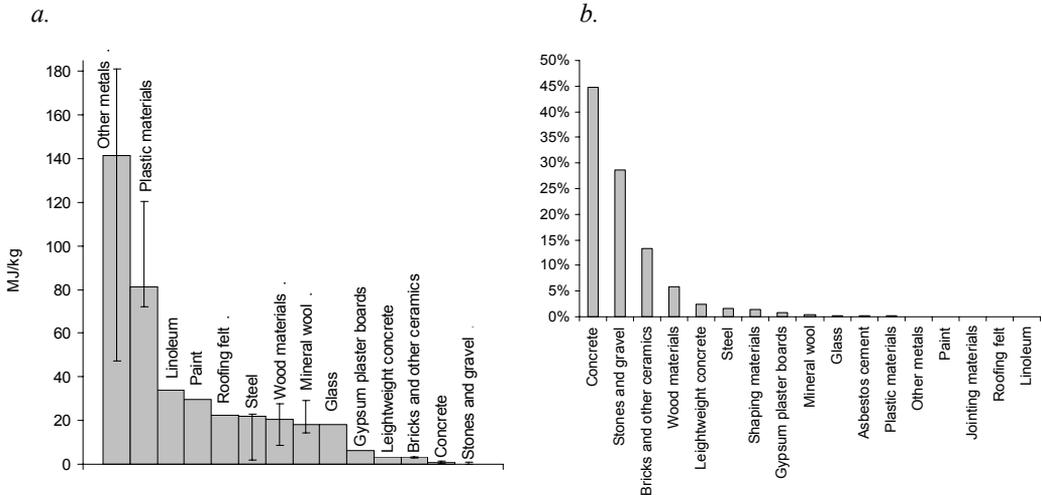


Figure 2. a) An indicator based on embodied energy coefficients. The products' and materials' embodied energy coefficients were weighted (based on mass) into larger material categories. The interval shown for each category represents the products having the smallest and the largest individual embodied energy coefficients. b) The mass-based indicator shows the share of each material category of the total amount of materials in the building stock.

The final result (Figure 3) was an indicator combining the weighted embodied energy coefficients (Figure 2a) in a product with the total amount of each material category (see Table A1 in the paper) and normalizing the same for the materials' service life (see Table A1 in the paper). This represents the embodied energy normalized for service life in the Swedish building material stock. Wood materials ranked the highest, as the most energy-intensive group of building materials. Next came bricks and other ceramics, concrete, and then steel, presented according to decreasing embodied energy. The remaining material categories each represented a 5% or smaller share of this indicator (Figure 3). The material categories are composed of several materials and products; the dominating material or product representing the category wood materials was about 60%, in terms of this embodied energy indicator, untreated wood. Concerning bricks and other ceramics, almost 90% was common bricks. The concrete category contained 50% cast-in-situ and 50% prefabricated concrete. For the category steel, the alloyed steel represented 89%.

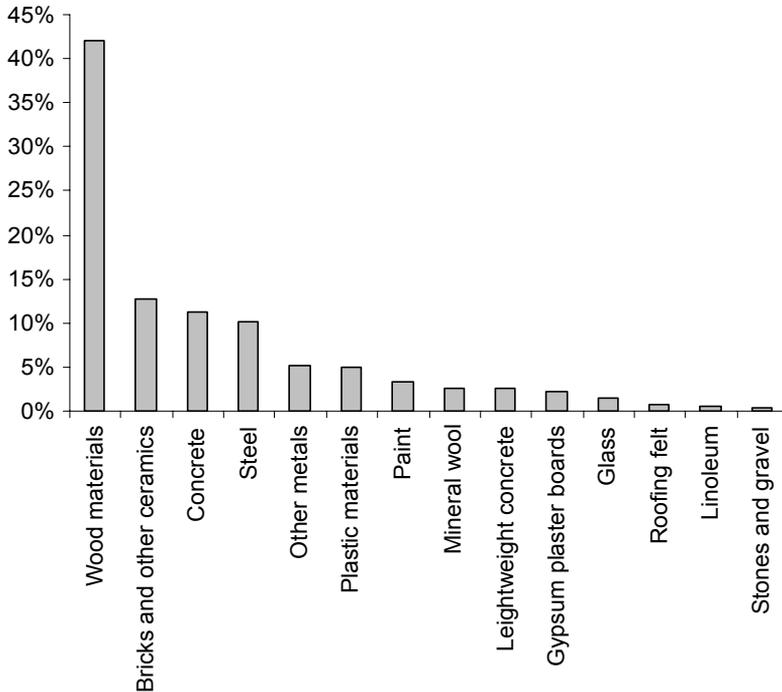


Figure 3. The share of total embodied energy of the building material stock for the studied material categories normalized with the expected service life for each product.

To test the robustness of the ranking, a sensitivity analysis was performed by varying the embodied energy coefficient, the mass-based indicator or the service life, one at a time. In all cases it resulted in the same top ranking of wood materials as in the original calculation, and the other material categories varied between first and third place in the ranking list. Therefore the main result was considered to be fairly reliable.

### Environmental analysis of reuse of cast-in-situ concrete in the building sector (Paper V)

The recirculation studied in this paper represented 80% of the entire concrete frame structure in the new building, excluding the bottom slab that was constructed from virgin concrete. This case was compared to a theoretical construction made of virgin raw materials considering energy use (Figure 4) and emissions of carbon dioxides (CO<sub>2</sub>) and nitrogen oxides (NO<sub>x</sub>) (Figures 5a & 5b).

These calculations clearly show that recirculation was beneficial compared to the use of virgin materials considering energy use and emissions of carbon dioxides (Figure 4; Figure 5a), while it was less beneficial for emissions of nitrogen oxides (Figure 5b).

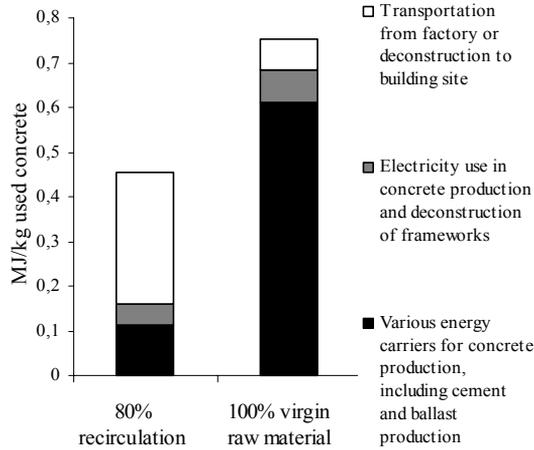


Figure 4. Energy use during the life cycle of concrete from cradle to building site. The use of virgin concrete results in high energy use. Also the transportation of concrete elements on long-distance trucks is shown to be a large part of the energy use for recirculation.

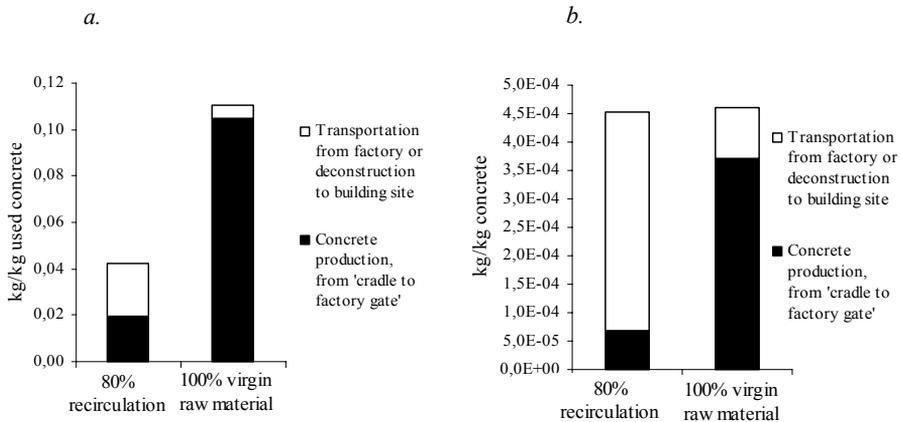


Figure 5 a & b. Emissions of CO<sub>2</sub> and NO<sub>x</sub>, respectively, for the activities related to concrete production from cradle to gate and the transportation of concrete from decon-

*struction site or factory to the building site. The transportation of recirculated concrete to the building site represented a large part of the studied emissions.*

It was concluded that transportation distances are important for the overall environmental performance since emissions of NO<sub>x</sub> in the studied case were in the same magnitude as the reference case (Figure 5b). Therefore, to achieve environmental benefits for this environmental category the transportation by truck should not be too far.

### Recirculation, upgrading, cascading of building materials - What is the difference? (Paper VI)

The different environmental outcomes of recirculation, upgrading and cascading in the studied cases are not entirely consistent. Considering cast-in-situ concrete, the differences between recirculation, upgrading and cascading for the studied cases were small (Figure 6a). However, they were energy saving, about 100 MJ/tonne of final building elements, compared to virgin raw materials. The net energy savings for recirculation of prefabricated concrete was large, about 1000 MJ/tonne of final building elements (Figure 6b), while upgrading and cascading was in the same magnitude as reuse of cast-in-situ concrete. Considering reuse of clay bricks (Figure 6c) the energy savings increased with the degree of conservation of inner material structure compared to the use of virgin materials.

One reason why recirculation of cast-in-situ concrete is not more net energy-saving than other reuse options was that the studied building projects were complemented with virgin materials in order to fulfil the present Swedish building norms. These auxiliary materials, mainly gypsum boards, angle iron, wooden bars and mineral wool, added so much energy to the reuse projects that the potential environmental benefits were not realised. This finding implies that the building techniques have to be developed if recirculation is to be environmental beneficial. On the other hand, recirculation of prefabricated concrete contributed to net energy savings despite the large amounts of auxiliary materials used (Figure 6a). This difference depends mainly on the large amount of energy required for the upstream and manufacturing processes of prefabricated concrete from virgin materials, more than twice the amount as for cast-in-situ concrete.

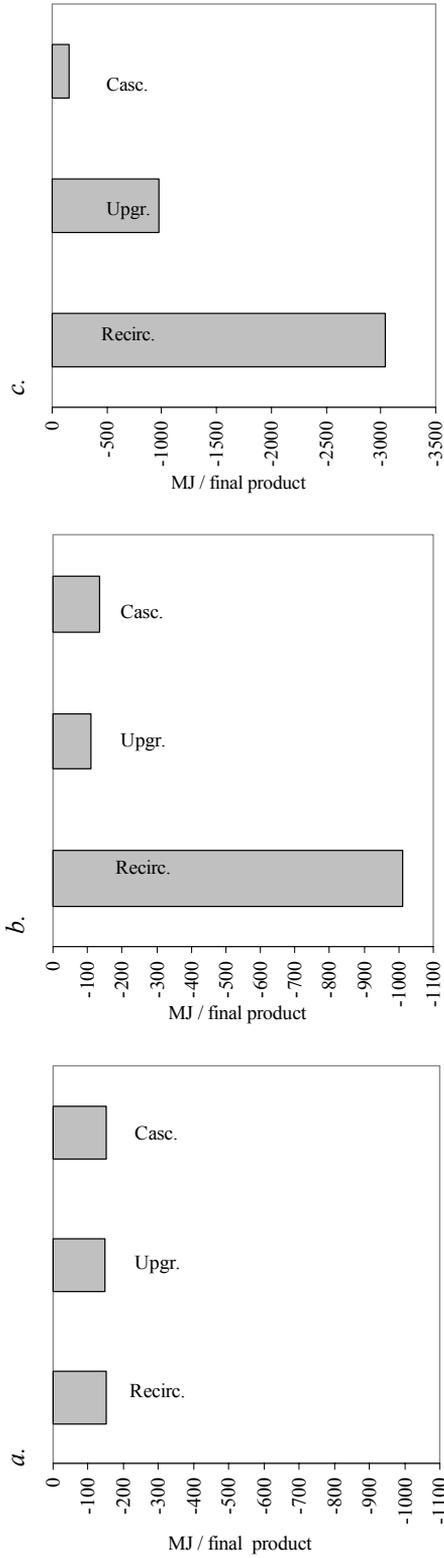


Figure 6. A comparison between recirculation, upgrading and cascading showing the net energy use for reuse of (a) cast-in-situ concrete, (b) prefabricated concrete and (c) clay bricks, respectively. The functional unit in this accounting was 1 tonne of the final products, fulfilling the current Swedish building norms. Please notice the different scales between the concrete alternatives and clay bricks.

## Synthesis

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The aim of this part of the thesis is to emphasise what has been learned looking at all papers together. To facilitate this analysis, the papers are here related to the structural components of the developed framework for environmental assessments in Paper II: i) assessment levels, ii) issues addressed, iii) applied methods and iv) results of the studies (Table 3).

### Assessment level

Most of the studies in this thesis deal with the narrow life-cycle level (Table 3). This approach should be seen as a complement to the mainstream environmental assessments of reuse of construction materials that mainly address the material level and occasionally the local environment level. The narrow life-cycle level additionally includes material and energy resource aspects and global environmental issues besides the pollution aspects of the nearby environment (Table 1) that have been thoroughly addressed by other researchers. Another reason to apply the narrow life-cycle level was the ambition to test simple and simultaneously environmentally relevant methods.

A simplified life cycle approach is applied for the environmental assessment in Paper VI. However, the system boundaries are close to those exemplified for the industrial system level in Figure 1 including crediting of avoided processes.

There are fundamental differences concerning the assessment levels between the papers, not emphasised in Table 3. Firstly, the assessment levels are chosen deliberately in Paper II-IV and in the environmental assessments in Paper V and VI. Yet, considering Paper I, the assessment level is a consequence of the governmental directives to the studied organisations and their performed environmental management.

An important consequence of deciding system boundaries, i.e. what to include and exclude, which also decides the assessment level, is to be aware of which questions could actually be addressed within the desired boundaries.

Table 3. An overview of significant components of the papers in relation to the assessment framework.

	Paper I	Paper II	Paper III	Paper IV	Paper V	Paper VI	
Assessment levels	<ul style="list-style-type: none"> <li>Local environment</li> <li>Narrow life cycle</li> </ul>	<ul style="list-style-type: none"> <li>All levels discussed</li> </ul>	<ul style="list-style-type: none"> <li>Narrow life cycle</li> </ul>	<ul style="list-style-type: none"> <li>Narrow life cycle</li> </ul>	<ul style="list-style-type: none"> <li>Narrow life cycle</li> </ul>	<ul style="list-style-type: none"> <li>Narrow life cycle / industrial system level</li> </ul>	
Issues addressed	<ul style="list-style-type: none"> <li>Implementation of SIE</li> <li>Measures in environmental management</li> <li>Material and energy flows</li> </ul>	<ul style="list-style-type: none"> <li>Different assessment methods</li> <li>System boundaries</li> <li>Pollution and resources aspects</li> </ul>	<ul style="list-style-type: none"> <li>Energy indicator for environmental pressure</li> <li>Implications for use</li> </ul>	<ul style="list-style-type: none"> <li>Material and energy resources perspective</li> <li>Prioritising building materials</li> </ul>	<ul style="list-style-type: none"> <li>Environmental assessment of recirculation of cast-in-situ concrete</li> </ul>	<ul style="list-style-type: none"> <li>Comparison of recirculation, upgrading and cascading</li> <li>Building projects involving reuse</li> </ul>	<ul style="list-style-type: none"> <li>Comparison of recirculation, upgrading and cascading</li> <li>Building projects involving reuse</li> </ul>
Applied methods	<ul style="list-style-type: none"> <li>Characterise measures in inflows, outflows and stock for life cycle</li> <li>phases of construction, management, use and end-of-life</li> </ul>	<ul style="list-style-type: none"> <li>Comparing environmental assessment methods regarding different system boundaries</li> </ul>	<ul style="list-style-type: none"> <li>Calculating energy use's share of total environmental pressure</li> <li>Characterising an energy indicator's possibility to reflect environmental pressure</li> </ul>	<ul style="list-style-type: none"> <li>Calculating embodied energy in building material stock</li> <li>Normalizing with service life</li> </ul>	<ul style="list-style-type: none"> <li>Life-cycle-based comparison of recirculation of concrete frame structure to the use of virgin raw materials</li> <li>Energy use, CO<sub>2</sub> and NO<sub>x</sub></li> </ul>	<ul style="list-style-type: none"> <li>Accounting for primary energy use in a life-cycle perspective</li> <li>Comparing with reference cases of virgin raw materials</li> <li>Calculating net energy savings</li> </ul>	<ul style="list-style-type: none"> <li>Accounting for primary energy use in a life-cycle perspective</li> <li>Comparing with reference cases of virgin raw materials</li> <li>Calculating net energy savings</li> </ul>
Results of the studies	<ul style="list-style-type: none"> <li>Main focus on management of infrastructure</li> <li>Material inflows quantified</li> <li>Material outflows prioritised for mitigation measures</li> <li>Reuse touched upon in action plans, not applied in a large scale</li> </ul>	<ul style="list-style-type: none"> <li>Framework for environmental assessment of use of materials</li> <li>Widening the system boundaries in environmental assessments</li> </ul>	<ul style="list-style-type: none"> <li>Strong reflection of e.g. depletion of fossil fuels &amp; climate change</li> <li>Weak reflection of e.g. depletion of metals, minerals, biotic resources and stratospheric ozone</li> <li>The use of energy indicators should be followed with a discussion of their validity</li> </ul>	<ul style="list-style-type: none"> <li>Order of priority: wood materials, bricks and other ceramics, concrete and steel.</li> <li>Measures for policy-making</li> </ul>	<ul style="list-style-type: none"> <li>Recirculation was preferable compared to virgin raw materials</li> <li>Transportation distance with trucks resulted in limited environmental benefits</li> </ul>	<ul style="list-style-type: none"> <li>Recirculation was preferable compared to virgin raw materials</li> <li>Transportation distance with trucks resulted in limited environmental benefits</li> </ul>	<ul style="list-style-type: none"> <li>Net energy savings in all cases</li> <li>No consistent differences among recirculation, upgrading and cascading</li> <li>Savings increase with conservation of inner material structure for clay bricks</li> <li>Auxiliary materials represent a large part of total energy use</li> </ul>

## Issues addressed

The focus of this thesis was the reuse of construction materials in societal industrial ecology (SIE). These activities take place in industrial and societal systems that include many different actors and interests. A common societal ambition is that reuse should contribute to a better environment and saving natural resources. Consequently, the research was focused on assessing environmental performance, especially material and energy resources, of reuse measures (Table 3).

The framework for environmental assessment was developed for the use of industrial by-products in road structures (see Paper II). However, if more generally formulated it could be a relevant typology of environmental assessments. It could support studies of both resources and pollution aspects and could also encompass different perspectives and interests (Table 1, Paper II).

## Applied methods

The developed assessment framework emphasises what could be studied by applying different system boundaries and could therefore facilitate choice of methods and approaches in the scoping process of environmental assessments. Characteristics of the applied methods in this thesis can be summarised as follows: Simplified models of material and energy flows in a life-cycle perspective using indicators such as primary energy use (Table 3). The methods mainly answer questions about the environmental performance of material and energy use applied at the narrow life-cycle level. Because several actors are involved in reuse activities it is an allocation problem to fairly distribute environmental pressures over products and processes (Ekvall and Tillman, 1997; Finnveden, 2000; Ekvall and Finnveden, 2001). In this thesis earlier environmental pressure upstream from the reused materials was consequently excluded. This allocation means to consider that the alternative to reuse would have been depositing in a landfill (cf. Weidema, 2001).

To be able to thoroughly address the industrial system level there is a need for further development of assessment methods in order to, for example, reach consensus of allocation principles.

## Results of the studies

It was concluded that environmental performance of reuse could be beneficial under certain conditions (Papers V & VI). Two important factors influencing environmental performance of reuse are transportation by truck and auxiliary materials used in recirculation projects. Further, as a result of Paper II it could also be concluded that applying narrow system boundaries could exclude the potential benefits of reuse. For instance, the material level could not address issues of material and energy resources and global environmental pressure such as climate change. The methods applied to study reuse are important for the outcome of environmental assessments and consequently for the ultimate environmental performance of reuse.

## Discussion

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The discussion includes my reflections on reuse in society and how to environmentally assess it, considering the studies performed.

### Conditions influencing environmental performance

In order to meet the ambitions of societal industrial ecology (SIE), reuse could be one measure for resource-saving materials and energy use (Paper VI). However, it is important to discuss which reuse options could be appropriate and to environmentally assess them.

The energy invested in the materials from cradle to building product is largely impossible to recover, except in recirculation and partly in upgrading, or when there is fuel energy potential of raw material feedstock, which at least could be utilised in combustion plants with heat recovery. Considering that most of the construction materials used, with respect to the quantity in the building stock, are inert materials and also nonrenewable (Paper IV), it is important to utilise the product for as long as possible in the first place and reuse the material in the second place, i.e., considering measures such as recirculation and upgrading. Recirculation is the most energy saving, at least for concrete and clay bricks (Paper VI).

Therefore, it is important to recirculate rather than cascade materials in order to conserve their inner material structure (cf. Connelly and Koshland, 1997) and thereby increase the net energy savings (Paper VI). Consequently, the large amounts of energy-intensive auxiliary materials utilised in the recirculation building projects studied in this thesis should be minimised. A complementary measure to facilitate recirculation would be to design for future disassembly and reuse (Thormark, 2001b). Further, a reasonable assumption is that easily deconstructed buildings could be economically competitive to new production, which could be a prerequisite for the increased reuse of construction materials in society (cf. Thormark, 1997; Eklund et al., 2003).

If both auxiliary materials and transportation distances could be minimised, the probability of accomplishing reuse might increase. Less energy used for auxiliary materials may then also contribute to elucidation of the differences among recirculation, upgrading and cascading processes (cf. Paper VI). Even though all studied reuse alternatives were shown to be energy

saving, the potential substitution of virgin raw materials by reuse would be higher for recirculation than for upgrading and cascading. Upgrading processes could be less energy demanding than the production from virgin materials (Paper VI), since a smaller amount of natural resources need to be extracted. Cascading still requires virgin materials and energy for continued production of the original product upstream from the cascading process.

### *Policy implications*

The prioritising procedure developed in Paper IV to point out the most significant material and energy-related building materials used in society could be beneficial for policy-making. As an example, The Ecocycle Council for the Swedish Building Sector has pointed to resource-saving materials and energy use as two of the four prioritised goals (The Ecocycle Council for the Swedish Building Sector, 2003). In the work to achieve these goals this prioritising could be helpful when materials are selected. Also for the Swedish National Rail and Road Administrations, respectively, ranking energy-intensive materials may be helpful in prioritising measures of material flows in societal industrial ecology in environmental management.

A similar prioritising procedure for railway-specific materials in infrastructure was performed by Svensson and Eklund (Submitted). They concluded that steel and iron products, a few percent of the total material use, contributed to almost 80% of the total material-related energy use in a life-cycle perspective of the railway infrastructure, excluding the transportation of trains. Concrete represented the largest bulk material, more than 90%, but less than 10% of the total material-related energy use. These results were then argued to be an important component in the long-term planning of environmental management (ibid.). The prioritising in Paper IV and the method by Svensson & Eklund (Submitted) could mainly be useful for national priorities and complex systems.

Another approach to prioritisation is described in Hansen (1995). This methodology ranks manufacturing products (or product groups) by summarising the individual ranks of energy use and material resource loss, respectively. This approach gives high priority to energy-intensive materials, nonrenewable materials and materials or products that are not currently reused. Moreover, an additional method for prioritising building materials

could be LCA, which gives a more comprehensive picture of the materials' environmental pressures. Further, an option in prioritising national issues could be to use input-output-based LCA models for the construction sector, as Treolar et al. (2000) do. They argue that their hybrid LCA method could take the currently missing upstream, direct and indirect environmental pressures into account. However, Paper IV in this thesis utilise a simplified prioritising approach in order to point out the most significant building materials on national scale.

Societal industrial ecology (SIE) provided a holistic view of environmental issues, according to the respondents at the Swedish National Rail and Road Administrations (Roth and Eklund, 2000). Therefore, SIE would have the potential to propagate into the work of overall environmental management. However, looking at the implementation of SIE as applied to management of the rail and road infrastructure, respectively, the holistic view was not implemented (Paper I). This was studied using the material flow perspective, which could provide a comprehensive picture of material and energy resources in environmental management. Applying the material flow perspective could then be beneficial in studying resource aspects of reuse and in implementation of SIE.

Reducing the construction materials' embodied energy intensity may not be an issue for the building and construction sector alone and could involve other industries and societal policy-makers, as well. Improve the resource economy of construction materials could, for example, also be effected by governmental economic instruments, such as taxes, on the use of virgin material (cf. Bruvoll, 1998). Further, the development of systems for material recirculation and design considerations is also in the interest of the final user, who would have performance requirements for the final product.

#### *Methodological considerations in decision-making*

If the decision-making authorities required environmental assessments coping with broader perspectives, the assessments might develop to also address the narrow life cycle and industrial system levels. Widening the system boundaries of environmental assessments is principally the same as system expansion in the allocation procedure in LCA. Wider system boundaries as well as system expansion have the purpose of including co-products and processes that affect the study object (cf. Weidema, 2001; Rebitzer et al., 2004). Therefore, widening the system boundaries in present

mainstream environmental assessments of such materials as industrial by-products, would take into account not only the environmental pressure of the material itself, but also issues such as substitution of virgin raw materials and climate change.

Applying environmental assessments addressing a broader set of environmental pressures could contribute to a broader basis for decision-making. Environmental assessments that apply narrow system boundaries address few environmental issues and involve prioritising the issues that are considered most important. Wider system boundaries give increased knowledge of environmental benefits and drawbacks, which might change which reuse alternatives could be considered as favoured. However, the final decision on which alternative to choose is contingent upon values and also depends on other aspects than environmental. It is only one dimension of the decision-making processes taking place in society. To conclude, environmental assessments broader in scope may indirectly facilitate the accomplishment of reuse of construction materials.

As the developed framework for environmental assessments promotes the use of several perspectives and assessment approaches, it is required that knowledge and competence are available in the analysis team. Consequently, applying several of the system levels could require much time and personnel for discussing scope and system boundaries, collecting data and carrying through several studies. However, applying system boundaries that address various issues has the advantage of requiring the use of several environmental tools that counteract side effects and problem shifting.

### Reuse of construction materials in a life-cycle perspective

In order to find simplified methods considering relevant environmental performance, compensating for the risk of problem shifting and simplicity is a difficult balancing act. On one hand, wider system boundaries widen the scope of environmental assessments and could include several perspectives and issues (Paper II). On the other hand, they require more time and competence. A fruitful way to deal with this may be to carefully use simplified versions of complex methods and thus cope with wider assessment levels. There are, for example, several methods for performing simplified LCAs (cf. Graedel, 1998; Todd and Curran, 1999; Hochschorner and Finnveden, 2003), yet no general method for this procedure (Rebitzer et al., 2004). An example of a vigorous reduced environmental assessment that still copes

with the narrow life-cycle level is the use of energy as an indicator for environmental pressure during a life cycle. In Papers V and VI the energy indicator was applied to the study of reuse of construction materials. Applying an energy indicator to studying bulk materials such as construction materials has been shown to be environmentally sufficient (cf. Svensson, 2005). Since the main emphasised benefit of reuse is resource-saving material and energy use, which is fairly reflected by an energy indicator (Paper III), simplifying the environmental pressure of construction materials into a single indicator was considered sufficient.

The methodological consequences of the boundaries selected in Paper V were that earlier environmental pressure was fully allocated to processes not included in the study. Additionally, the life cycle of reused concrete was not credited for avoided processes such as virgin production of concrete and landfilling the materials. This means that processes both favourable and unfavourable for the reuse case were excluded. The calculations showed that reuse of cast-in-situ concrete was clearly environmentally preferable for energy use and emissions of CO<sub>2</sub>, while reuse had similar performance as the reference case for emissions of NO<sub>x</sub>. Considering the problem of allocation of environmental pressures that took place 40 years ago, it was unattainable to estimate whether the excluded earlier environmental pressure and the avoided processes would equal each other in the assessment. Nevertheless, this is an example of how overly narrow system boundaries complicate the interpretation of the results. Moreover, the study in Paper V was applied with a wider scope including also the use of auxiliary materials in Paper VI, crediting reuse for avoided processes. These calculations resulted in the conclusion that reuse is energy saving for all studied cases still, the net energy savings were smaller than in Paper V. Therefore, the outcome of a study and the conclusions about the environmental benefits of a project partly depend on how the system boundaries are drawn (cf. Weidema, 2001). The interpretation of environmental performance is also a consequence of which environmental aspects are considered most important (cf. Finnveden, 2000). This is mainly a political act, but by including or excluding certain aspects, the environmental assessment indirectly affects what the outcome of a situation involving decision-making or planning could possibly be.

The site dependency of the local environment level could be lost when applying the life-cycle-adapted tools at the narrow life-cycle level. This mainly depends on the parameters addressed and their significance for the

local environment. There are, however, researchers that work on including sitedependency in the LCA procedure (cf. Potting et al., 1998). Another way to deal with the lack of site dependency is to apply studies at several levels. One example is McEvoy et al. (2004), who addressed the local environment level and the narrow life-cycle level by applying a mass-balance approach in a life-cycle perspective.

## Conclusions

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The most important findings from the studies in this thesis, considering environmental performance of reuse of construction materials and the assessment methodologies, are outlined here:

- Several factors influence the environmental performance of reuse of construction materials in the individual case. Generally, it is essential to environmentally assess and compare reuse measures.
- The system boundaries of the material level and the local environment level are the most appropriate for studies of pollution aspects of the reuse of by-products, because they involve a local focus. On the other hand, studies performed at the narrow life-cycle level and at the industrial system level could instead include the utilisation of natural resources and other environmental issues. Compared to the current mainstream environmental assessments of reuse mainly addressing the material level, the wider assessment levels provide a holistic approach to the study of environmental performance of reuse. What is included in an environmental assessment is significant for its outcome, i.e. the ultimate environmental performance of reuse depends on what is included in the environmental assessment.
- Studying the implementation of societal industrial ecology (SIE) revealed the lack of a consistent approach to the management of stocks, in- and outflows of the Swedish National Rail and Road administrations, though such an approach is present in the SIE concept, which was commissioned to be implemented on the transportation infrastructure.
- It is a balancing act to choose simplified methods that address relevant environmental performance and that simultaneously could compensate for the risk of problem shifting. A fruitful way to deal with this might be to carefully use simplified versions of complex methods and thus cope with wider assessment levels. An example of a drastically reduced environmental assessment that still addresses the narrow life-cycle level is the use of energy as an indicator for environmental pressure during a life cycle.

Energy use is a particularly relevant indicator in environmental management and research in the building, construction, transportation and energy sectors.

- The prioritising procedure developed to point out the most significant material and energy-related building materials used in society could be beneficial for policy-making. For example, in the work to achieve resource-saving materials and energy use, this procedure could be helpful when materials are selected. The most significant materials to consider are: wood, brick and other ceramics, concrete, and then steel, presented according to decreasing embodied energy of the Swedish building stock.
- Applying different system boundaries to study recirculation of cast-in-situ concrete exemplified how different system boundaries generate different results. By using a narrower life-cycle approach, showed that recirculation was energy saving compared to the use of virgin materials. When wider system boundaries were applied, the results showed less energy savings.
- Different reuse measures are currently being explored in society. Considering the reuse cases, recirculation of concrete and clay bricks was the most energy saving, followed by upgrading and cascading those materials. The different environmental outcomes of recirculation, upgrading and cascading in the studied cases are not entirely consistent. For example, recirculation is not more net energy-saving than other reuse options of cast-in-situ concrete. One of the reasons was that the studied building projects were complemented with virgin materials in order to fulfil the present Swedish building norms. These auxiliary materials added so much embodied energy to the reuse projects that their potential environmental benefits were not realised. This finding implies that the building techniques have to be developed if recirculation is to be environmentally beneficial.
- It was concluded that environmental performance of reuse could be beneficial under certain conditions. Two important factors influencing environmental performance of reuse are truck transports and auxiliary materials used in recirculation projects.

## Future research

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There are several areas that would benefit from further research related to the issues addressed in this thesis. For example, environmental assessments of reuse of construction materials that could cope with the industrial system level, a level not thoroughly addressed here, would add more knowledge to the reuse of construction materials. It would also be interesting to environmentally assess recirculation, upgrading and cascading for other construction materials, such as industrial by-products, wood materials and steel. Considering reuse of construction materials in general, it would also be interesting to more deeply examine material and energy flows of substitution of virgin raw materials, both upstream and downstream of the reuse processes.

Another research area that has been thoroughly addressed by researchers is the use of indicators, considering their economy and also sustainability aspects. However, considering the use of primary energy as an indicator it would be profitable to more deeply research and understand which environmental indicators would complement energy use in a fruitful way, depending on aim and application.



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## Personal communication

Carlfjord, P. NCC, Linköping, Sweden

Fredriksson, J. Sundbaum Byggprojekt AB, Linköping, Sweden

Starkenbergh, G. BEFAB Konsult AB, Mjölby, Sweden