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Life-Cycle Considerations for Environmental Management of the Swedish Railway
Infrastructure

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Railway Infrastructure

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Abstract

The aim of this thesis has been to develop an approach for the scoping of environmental aspects regarding material use in the Swedish railway infrastructure in order to contribute to strategic environmental management. This is done through the development of a method based on the concepts of embodied energy and material flows, which is then tested for its robustness. Furthermore, a study has been made on which preconditions for life-cycle considerations there are for the manager of the Swedish railway infrastructure and how this relates to the actual environmental pressures from the product. The study has used the Swedish National Rail Authority, Banverket, as a case.

First the environmental context was studied by an analysis of how the environmental pressure from material use compares to the operations phase and to other transport systems. Secondly, a scoping method for environmental pressure from material use in a large organization was developed and tests performed on its use and its robustness. Special focus was on the importance of materials transports and the environmental relevance of the energy indicator used. Finally, an organizational context was presented which showed the possibilities and hindrances to implementing life-cycle considerations in the environmental management of the Swedish railway infrastructure.

It seems difficult to incorporate life-cycle considerations in an organization whose history is characterized by its work on solving specific local environmental issues. In addition, there seem to be limited pressures either from outside or inside the organization to adopt life-cycle environmental management. There is a need for clearer and more specific policy instruments governing many of the global environmental issues pertaining to upstream environmental pressures in order to make it easier for organizations to translate these into something useful in their environmental management. The departments with the most capacity to influence the environmental pressures from material use are demanding support and more knowledge about life-cycle considerations in order to set more relevant environmental requirements on the products.

The perceived environmental advantage of the rail transport sector over road transports should not be taken for granted. The importance of the indirect

environmental pressures for the rail infrastructure decreases this advantage, since its material-related energy use is almost entirely from non-renewable sources. Thus the rail transport sector needs to start decreasing the use of energy for production of railway infrastructure products or its reliance on nonrenewable energy sources for production.

In order to start working with the environmental management of the railway products there is a need to adopt and introduce new perspectives. The approach developed in this thesis can be used to introduce these new perspectives, such as upstream environmental pressures, to the organization's environmental management. It can also be employed to identify hot spots in the organization's material use. Consequently, this new knowledge can be used in the design of new products, to set environmental demands in purchasing, and to focus further environmental analyses of the hot spots. It can also be used to broaden the perspectives in, for instance, environmental impact assessments, strategic environmental assessments and environmental reviews. The relative ease with which this indicator is collected and calculated can make it possible for the organization to include new environmental dimensions in their environmental management, which could otherwise be outside their expertise, budget or time frame.

The scoping of environmental pressures, by using the approach presented in the thesis, pointed to three important railway infrastructure products. These are the products that Banverket needs to focus on first. One of the most important tasks in incorporating life-cycle considerations for products is to set environmental requirements when introducing new products to the material supply process. The requirements should already be present in the design phase of the products. Thus it is essential that the product developers get the support needed in finding relevant environmental criteria for the new product. One way to accomplish this is to employ an environmental coordinator with sufficient knowledge in the technical departments to work together with the design teams as an integral part of the design process.

The overall environmental pressures from the railway transport system depend substantially on the upstream environmental pressures generated by the production of the infrastructure products. These pressures are totally dominated by three products. There is a large improvement potential in focusing the environmental management on these products by posing environmental requirements on their suppliers, in order to decrease the overall environmental pressures generated by the railway transport system.

Sammanfattning

Syftet med den här avhandlingen är att förbättra möjligheter till miljöledning av järnvägens infrastruktur genom att utveckla en metod för att rikta in ansträngningar på att minska miljöpåverkan från infrastrukturens produkter. Metodens används i ett byggprojekt och dess robusthet blir testad. Den använder den materialrelaterade energianvändningen för att studera miljöpåverkan från infrastrukturen. Vidare studeras vilka förutsättningar och hinder det finns för att införa ett livscykelperspektiv i Banverkets organisation.

Först analyserades de miljömässiga förutsättningarna genom en jämförande studie med vägtransportsystemet. Fokus låg även på infrastrukturens del i miljöpåverkan i jämförelse med själva transportererna i de bägge systemen. Sedan presenterades metoden och analyserades med avseende på användbarhet och robusthet. I de senare testen gavs materialtransporternas del av miljöpåverkan samt energiindikatorns miljörelevans extra utrymme. Slutligen studerades de organisatoriska förutsättningarna för att introducera metoden och införa ett livscykelperspektiv vid materialhanteringen.

De organisatoriska förutsättningarna präglas mycket av Banverket miljöhistoria som främst handlar om miljögifter kopplade till lokala eller regionala miljöproblem. Dessutom finns det få miljörelaterade krav utifrån, vilket delvis kan förklara att livscykelperspektivet i mångt och mycket saknats inom organisationens materialhantering. Miljökraven på Banverkets inköp av produkter är oftast lagkrav, men eftersom de lagkrav som har anknytning till de globala miljöproblemen, vilka främst kan kopplas till uppströms produktframställning, inte är tillräckligt specifika, har organisationen svårt att översätta dessa till relevanta miljökrav vid upphandling. De avdelningar inom Banverket som är mest berörda av upphandlingen och arbetet med kravspecifikationer kräver mer stöd och kunskap för att kunna införa livscykelperspektivet i materialhanteringen.

De upplevda miljöfördelar som järnvägen tycks ha över vägtrafiken är inte helt självklara. Vikten av indirekt miljöpåverkan från infrastrukturen är större för järnvägstrafiken än för vägtrafiken och detta i kombination med att den materialrelaterade energianvändningen är nästan uteslutande fossilbaserad leder till att miljöförspåranget minskar jämfört med trafikens miljöpåverkan. Om vägtrafiken minskar sitt fossilberoende i

användningsfasen så måste järnvägssektorn antingen minska energianvändningen eller fossilberoendet i produktionen av järnvägsprodukter för att fortfarande kunna sägas ha miljöfördelar. För att kunna göra det senare måste nya perspektiv introduceras i Banverkets organisation. Metoden som presenteras i denna avhandling kan användas för att introducera dessa nya livscykelperspektiv och bidra till att Banverkets ansträngningar fokuseras på att minska infrastrukturens miljöpåverkan. Denna nya kunskap kan användas vid design av nya järnvägsprodukter och vid upphandlingen av dessa. Dessutom visar avhandlingen på var utförligare miljöanalyser av produkter kan behövas. Metoden använder en energiindikator för att uppskatta miljöpåverkan från materialanvändningen. Denna indikator är lätt att använda för miljöanalysen vilket gör det möjligt att enkelt introducera och inrikta livscykeltankandet i organisationens miljöledning. Något som annars kan ligga utanför dess expertis, budget och tidsresurser.

Metoden identifierar de tre produkter som är absolut viktigast att fokusera på om man vill minska miljöpåverkan från materialanvändningen i infrastrukturen. Dessa är räl, slipers och ballastmaterial där räl har överlägset störst användning av uppströms materialrelaterad energi. Genom att introducera miljökrav tidigt i designprocessen vid införande av dessa produkter kan stora miljövinster göras. Teknikavdelningarna samt upphandlarna behöver därför stöd för att introducera dessa starkare krav på uppströms miljöpåverkan.

List of publications

Appended papers

The thesis is based on the work described in the following papers, which are referred to by their Roman numerals in the text.

- I Svensson, N. Almgren, T. Collin, P. & Eklund, M. (Submitted). Energy Use and Carbon Dioxide Emissions From the Rail and Road Transport Systems - the Importance of Infrastructure.
- II Svensson, N. & Eklund, M. (Submitted). Scoping of Environmental Pressure by Screening of Products in the Swedish Railway Infrastructure - Implications for Strategic Environmental Management.
- III Svensson, N., Roth, L., Eklund, M. & Mårtensson, A. (2006). Environmental Relevance and Use of Energy Indicators in Environmental Management and Research. *Journal of Cleaner Production*. 14: 134-145
- IV Svensson, N., Eklund, M. & Svärth, K. (Submitted). The environmental importance of materials transports in developing infrastructure - Case of the Swedish Railway System
- V Svensson, N. & Eklund, M. (Submitted). Life-cycle considerations for environmental management of an infrastructure manager

Paper III was written by me and Dr Liselott Roth although some of the results were also contributed by Dr Mats Eklund and Dr Anders Mårtensson, who also gave guidance and support to the writing process. Furthermore, except for Paper III, I have written all the papers myself with guidance, support and feedback from my supervisor Dr Mats Eklund.

For Paper I, Tomas Almgren and Per Collin compiled much of the data under my supervision while I structured the data and wrote the article. For Paper IV, Karin Svärth compiled the bulk of the data under my supervision and also in this case I structured and made the data ready for the article.

Other related publications not included in the thesis

Svensson, N. & Eklund, M. (1999). Förstudie - Flöden och förråd av miljöskadliga ämnen i banvallar. Report to Banverket (in Swedish)

Svensson N. & Eklund M. (2002). Materialinventering och miljöanalys för järnvägens infrastruktur. Report to Banverket (in Swedish)

Eklund, M. & Svensson, N. (2003). Var i livscykelkedjan sker den största miljöpåverkan för produkter i järnvägens infrastruktur? Report to Banverket (in Swedish)

Svensson, N. & Eklund, M. (2003). Miljöarbetet i organisationen för Banverkets materialförsörjningsprocess. Report to Banverket (in Swedish)

Sundin, E., Svensson, N., McLaren, J., & Jackson, T. (2002). Material and Energy Flow Analysis of Paper Consumption in the United Kingdom, 1987-2010. *Journal of Industrial Ecology*; 5(3):89-105

Svärdh, K. (2006). Environmental Performance of the Rail Transport System in a Life-Cycle Perspective - The Importance of Service Life and Reuse in Sweden. Master Thesis. Linköpings Universitet¹

¹ The Master thesis was supervised by me.

Table of contents

1	Introduction	3
1.1	Aim of thesis	5
1.2	Banverket - the organization being studied	6
1.3	Scope of the thesis	7
1.4	Outline of the thesis	8
2	Theoretical framework.....	9
2.1	Positioning of the thesis	9
2.1.1	<i>The DPSIR framework.....</i>	<i>14</i>
2.2	Life-cycle considerations in organizations	14
2.3	Scoping environmental pressure	15
2.4	Environmental indicators in environmental management	16
2.4.1	<i>Energy indicators.....</i>	<i>17</i>
2.5	Transport research regarding environmental aspects from material use	18
2.6	Points of departure	19
3	Method	21
3.1	The research process	21
3.2	Building projects studied (Paper II and Paper IV).....	22
3.3	Development of the scoping method	23
3.3.1	<i>Material-related energy use.....</i>	<i>25</i>
3.3.2	<i>Studying the approach's robustness</i>	<i>27</i>
3.4	Using case studies	28
3.5	General applicability of the results	29
3.6	Summary of the contributions of the appended papers and the methods used .	30
4	Results from appended papers	33
4.1	How does the environmental pressure from material use compare to the operations phase and to other transport systems? (Paper I)	33
4.2	Scoping of environmental pressure from material use in a large organization (Paper II, Paper III and Paper IV)	36
4.2.1	<i>The environmental relevance of the energy indicator</i>	<i>40</i>
4.2.2	<i>The environmental importance of materials transports.....</i>	<i>42</i>
4.3	What are the possibilities for and hindrances to incorporating life cycle considerations in Banverket? (Paper V).....	43
5	Discussion.....	47
5.1	Strategic relevance of life-cycle considerations in the railway transport sector (Aim I).....	47
5.2	The applicability of the scoping approach (Aim II).....	48
5.3	Life-cycle considerations for environmental management in Banverket (Aim III)	50
6	Conclusions.....	55
7	Acknowledgements.....	57
8	References	59

1 Introduction

A challenge that faces society's political decision-makers is whether to invest money in the road or railway transport system. These investments have varied greatly over the years. One argument for or against investing in a certain transport system could be its inherent environmental pressures. Furthermore, on a personal or company level it is sometimes necessary to choose between two different transport modes for a certain activity. These decisions can be influenced by how the environmental pressures from that transport are perceived. Consequently, since the transport sector is closely linked to the environmental pressures caused by our society, numerous studies have been made regarding the contribution from different transport sectors to such pressures. However, the bulk of these studies only concern transportation, and thus omits the environmental pressures from the material use needed to support these sectors, i.e. building and maintaining the infrastructure (cf. Bouwman and Moll, 2002). Furthermore, there is a trend in the environmental debate that has shifted the focus from local or regional point sources of environmental pressures towards more global environmental issues. Some of these issues, such as climate change and acidification, are closely linked to energy use either in production of products or for instance the transport sector.

Regarding the railway, one of its main competitive advantages is that it is generally perceived to be the most environmentally adapted land transport mode (cf. Smith, 2003). Compared with road traffic, the railway in Sweden uses relatively little fossil fuels since it mainly uses electricity from hydro power and nuclear power. However, the perceived notion of the superiority of the railway in environmental terms seldom includes the environmental pressures related to the infrastructure. A Swiss study suggests that the railway infrastructure contributes to more environmental pressures than the road infrastructure (Maibach et al. 1999). Since the transport sector is very much linked with environmental pressures arising from direct energy use, for instance causing climate change, there is a need to address the indirect energy use from the infrastructure and to study the relations between the operations phase and the infrastructure.

In Sweden the railway infrastructure is managed by the Swedish National Rail Authority, Banverket, a governmental organization which also has

overall responsibility for the railway sector in Sweden. In 1996 Banverket received a governmental directive regarding the introduction of principles aimed at closing the material loops of the railway infrastructure, which led to an action plan being developed (Banverket, 1996). For environmental management to be effective and to work towards closing the material loop, there is a need to take into account both the inflow and the outflow of resources to the organization, and additionally the resource use inflicted by these flows upstream and downstream from the organization (O'Rourke et al., 1996). In this thesis this is called life-cycle consideration of environmental pressures. However, addressing the inflows has strategic implications, since problems related to outflows, like emissions and waste, could be decreased. The environmental measures and goals in Banverket are almost entirely dominated by measures regarding waste management and reuse, and very little actual focus on the resource dimension of the products that flow into the organization (Roth & Eklund, 2000a). However, the inflows to the railway infrastructure are at least indirectly monitored, since Banverket keeps track of its economic inputs to their building and maintenance projects.

In 1998, Banverket received a directive from the Swedish government to implement an Environmental Management System, or EMS (Swedish Government, 1998). Since then, some departments of this organization are working according to a certifiable EMS, while other departments are still struggling with its implementation. The environmental management of an organization is based on the environmental aspects highlighted in its environmental reviews. This is, for instance, relevant in the case of implementing a standardized EMS, in which case it is actually a prerequisite to performing an environmental review, and based on that, identifying which are the most significant environmental aspects of the organization (ISO, 1996; Ammenberg, 2003). The assessment of environmental aspects plays a key role in prioritizing and setting environmental goals (Johnston et al., 2000; Zobel & Burman, 2004). However, there is no standardized approach to identifying these environmental aspects (Ammenberg, 2003). The environmental aspects prioritized in environmental systems are often site-specific, and aspects such as product characteristics concerning resource use upstream and downstream from the site are generally not emphasized (Ammenberg & Sundin, 2005). Thus there is a lack of life-cycle considerations when doing the prioritizing.

To sum up, Banverket has an action plan regarding closing material loops but so far most of the work has been on the outflows of material from the infrastructure. In order to incorporate life-cycle considerations for the inflows of materials to Banverket, a scoping method will be proposed in this thesis. The term scoping that is used in this thesis is derived from the field of Environmental Impact Assessment (EIA). In the EIA process, scoping involves selection of key environmental impacts to focus on. In this thesis it refers to the process of identifying hot spots among environmental pressures from material use. Furthermore, there is a need to incorporate life-cycle considerations in Banverket's environmental management.

1.1 Aim of thesis

The aim of this thesis has been to develop an approach for the scoping of environmental aspects regarding material use in the Swedish railway infrastructure in order to contribute to strategic environmental management. This is done through the development of a method based on the concepts of embodied energy and material flows which is then tested for its robustness. Furthermore, a study has been made on which preconditions for life-cycle considerations there are for the manager of the Swedish railway infrastructure and how this relate to the actual environmental pressures from the product. The study has used the Swedish National Rail Authority, Banverket, as a case. A discussion is also made of the applicability of the results to other sectors.

The aim described above is in turn broken down into sub-aims to clarify and help structure the thesis. These are not presented in order of importance: Aim I sets the environmental context, Aim II concerns the development of the approach, and finally Aim III addresses the organizational context of the approach.

Aim I: To find how environmental pressure from material use in the railway infrastructure compares to the operations phase and to the road transport system (Paper I).

Aim II: Developing a scoping method for environmental pressure from material use in a large organization and to test its use and its robustness. Special focus has been on the importance of materials transports and the environmental relevance of the energy indicator used (Paper II, Paper III and Paper IV).

Aim III: To find what the possibilities and hindrances are to implementing life-cycle considerations in the environmental management of the Swedish railway infrastructure (Paper V).

1.2 Banverket - the organization being studied

The Swedish railway system consists of roughly 11,000 km of railway, of which about 9,000 are electrified. The railway infrastructure is owned by Banverket, while trains are operated by several different operators. Banverket has about 16,000 different railway-specific articles in use today, of which 5,000 are used frequently. Of these 5,000, about 400 are used routinely. A railway article in this case can be anything from a specific bolt or screw to posts and rails while I refer to products when the articles are grouped together (i.e the product *cable* consists of several *cable articles*).

The handling of these articles involves actors in and outside the organisation. First, there is the technical department at Banverket. This department is divided into four different parts, each responsible for a technical system: signalling, electrification, telecommunications, and the track. These technical departments produce the technical specifications for the products and approve each new product that is used in the railway. Secondly, there is the logistics department of Banverket, Materialservice, which distributes all the railway-specific products. Furthermore, they are responsible for the storage of products needed to maintain the railway. Thirdly, a very important actor is the purchasing department, which is also responsible for the communication of environmental requirements to the suppliers. They set up general agreements with the suppliers which regulate the prices and include technical specifications as well as some environmental requirements, mostly regarding hazardous substances. Then there are of course other important departments that act as support to the departments mentioned as well as divisions representing geographic regions which handle the everyday maintenance of the tracks. The support departments are the top-level management, the environmental unit and the unit for maintenance which are all situated at the headquarters of Banverket. Finally, another actor is the building contractors responsible for individual projects, who purchase and order bulk materials such as ballast materials and concrete building parts themselves. The latter are not classified as railway-specific products, but are still important for the assessment of the environmental performance of the railway since they constitute a significant material use in the railway.

The environmental work in Banverket up to the date of this study can be described as working more with specific problem areas rather than using strategic environmental management. This is in turn influenced by the environmental history of Banverket which is dominated in media coverage by the use of herbicides, creosote leakage from wooden railway ties and leakage of toxic substances in a tunnel project which got a lot of negative press and media attention. Consequently there has been a focus on limiting the use of hazardous substances and toxic substances in the organisation.

1.3 Scope of the thesis

This thesis studies the material use of the infrastructure products of the railway and their related environmental pressures. The main focus is on the resource perspective of the environmental pressures and as a result hazardous substances and toxic emissions are not discussed in depth. Instead they are touched upon when necessary to make comparisons to the environmental management of the material use. Furthermore, there is a higher level of inclusion of hazardous substance management in Banverket while the life-cycle aspects from resource use are not as developed. Another reason to focus on energy use is that the main political environmental issues of the transport systems are linked to resource use, namely the environmental pressures from energy use in operating the different transport modes, which is causing for example climate change. Thus, these are the issues that are often discussed when making important strategic policy decisions regarding transports in society. This scope is discussed further in the method chapter when the research process is outlined.

Banverket has had most of its attention on hazardous substances, toxic emissions and to some extent the outflow of materials from the organizations. This has led me to focus more on the inflow of materials and the associated upstream environmental pressures in developing the scoping method. However, end-of-life treatments are discussed briefly since these are connected to the environmental management of the material use in the organization. Furthermore, the omission of end-of-life treatments is discussed further in Paper I.

The thesis discusses different strategic environmental management options that can arise when life-cycle considerations are added into the organization. It does not go into detail as to which organizational changes might be needed and how these changes might be implemented in the organization.

Since one of the aims of the thesis is to develop an approach which should be used for environmental management by Banverket, the focus has been on a general picture of the material use of railway infrastructure. This means that I have excluded environmental pressures from tunnels and bridges since they are specific to each railway stretch. However, if the approach is later used for specific projects, there is nothing inherent in the method that excludes tunnels or bridges; instead it should be straight-forward to include them. This choice will be discussed briefly in the discussion.

1.4 Outline of the thesis

The first chapter gives an introduction to the problem area and sets the stage for the aim of the thesis which follows in a sub-chapter. The three sub-aims govern how the method chapter, the presentation of the results and the discussion are structured. The chapter also includes a short description of Banverket as well as a discussion of the scope of the thesis. The second chapter will present the theories which are used in the thesis and will end in the overall points-of-departures the thesis uses to discuss its results and which underlying assumptions and research areas have influenced the research performed. The method chapter will present the journey the author has traveled in order to reach this point where the thesis is made and the research process which has formed the basis of the aim of this thesis is shown. Then the case study projects which have been used in the different papers are presented. It also presents how the author has used an energy indicator as a simplified overall indicator of environmental pressures. Furthermore, it presents a discussion on using case studies in research and to what extent the results from this thesis can be generalized. The chapter finishes of with a short description of the methods used in the individual appended papers. This section is kept quite short since the methods are discussed more thoroughly in each separate paper. The fourth chapter presents the results pertaining to the sub-aims. Then follows a discussion which deals with how the results compare to other research as well as the relevance of the results for Banverket's strategic environmental management. After that the discussion is summarized in the conclusions of the thesis.

2 Theoretical framework

This chapter will outline the main theories used in this thesis. It will begin with a short introduction to important concepts related to the thesis subject in order to position it to other research. This is followed by a discussion of several related issues which form the points of departure for this thesis. Finally, the points of departure are summarized in order of clarity.

2.1 Positioning of the thesis

In an inter-disciplinary field such as environmental science there is always a need as a researcher to position the work in order for the potential reader to understand through which “eyeglasses” the research is viewed. There are many concepts which are of relevance to this research and in this and the following sections I will discuss how these concepts can be related to the work done for this thesis. Figure 1 depicts the concepts and methods which I have found especially relevant for my work. The concepts are all rather broad and to some extent overlap each other. I will start this chapter on my theoretical framework by giving a cursory description of them and then later in the chapter discuss more about specific issues to which they bring attention which are relevant to this thesis subject.

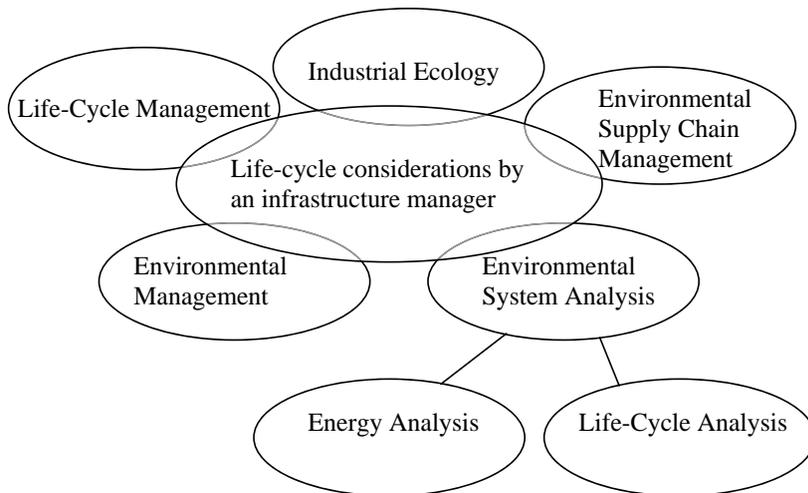


Figure 1: *Positioning of my research with related concepts and methods.*

The concept of industrial ecology emerged as a reaction to continued natural resource depletion and environmental impacts from resource use as well as pollution from industrial activities (O'Rourke, et al., 1996). It promotes a shift from “end-of-pipe” solutions towards more preventative and holistic solutions (ibid.).

Ehrenfeld (1994) has produced a list of the components he feels are essential for the concept of industrial ecology: 1) improving metabolic pathways for material use and industrial processes; 2) closing material loops in industry; 3) dematerializing industrial output; 4) systematizing patterns for energy use; 5) balancing industrial input and output to ecosystem capacity; 6) aligning policy to conform with long-term industrial system evolution; and finally 7) creating new action-coordinating structures, communicative linkages, and information.

In the list above, several components are relevant for this thesis in particular and material use in organizations in general. However, in order to take action regarding the different components of the strategy, it is essential that the organization gain knowledge of its material use in the first place. Cohen-Rosenthal (2004) suggests that before talking about material flows, there are two questions that need to be answered. First, “What are we using the materials for?” Second, “How can we reduce the material and energy use needed for the intended material use?” After that, states Cohen-Rosenthal, it is possible for an organization to know where to concentrate efforts, set up strategies and take measures to meet the challenge of improving the environmental performance of the system.

Life-Cycle Management (LCM) is a concept that tries to include life-cycle environmental criteria in an organization's strategies in order to reach business gains (Fava 1997). According to Linnanen et al. (1995), LCM consists of three views:

- 1) Management view - integrating environmental issues into the decision-making of the company;*
- 2) The engineering view - optimizing the environmental impact caused by the product during its life cycle;*
- 3) The leadership view - creating a new organizational culture. (ibid.)*

Furthermore, Hunkeler et al. (2003) defines LCM as an integrated system for improving operations, products, and services guided by a life-cycle

perspective in information and decision-making. They continue by saying that decision-making is often improved by giving the decision-makers better information (ibid.). With the definitions above, LCM has some interesting implications for this thesis. First, the reason for developing a method for scoping environmental pressure from products was to make it easier to integrate life-cycle considerations into Banverket. Secondly, the insights gained from the scoping will help the engineers at Banverket work towards optimization of the environmental impact from the material use. However, the thesis only briefly discusses what this means for the organizational culture.

Environmental Supply Chain Management (ESCM) can be described as activities which try to improve the environmental performance of purchased goods or of the suppliers which produce them (Bowen et al. 2001). Bowen (ibid.) further distinguishes between two types of ESCM, product-based green supply and greening the supply process. Of these two, the research behind this thesis lies closest to the first type since I do not go into detail about what the individual supplier needs to do, but rather what can be done with the specific products or goods.

Seuring (2005) discusses the differences and similarities between LCM, IE and ESCM and concludes that the first is focused on product design strategy, the second is more a natural systems vision and the latter implements an operational actor network. He also points out what they all have in common: that they use a systems perspective and that they all include material and energy flows and the actors influencing them.

According to Burström (2000), the term “environmental management” could be divided into two different meanings according to whether the emphasis is on the word environment or the word management. The former deals more with society’s management of the natural environment and the latter more with environmentally conscious management of society and/or organizations (ibid.). In terms of this thesis it is clearly the latter version which best describes the use of the term by me, i.e. in this thesis it is meant to be understood as a concept of how an organization can be managed in order to decrease the environmental pressures from its activities. This is a positioning and narrowing of the concept environmental management since environmental management using Burström’s definition is broader than how it is used in this thesis. In this thesis the concept is used with a direction

towards less environmental pressures, but in Burström's definition there is no direction stated.

In this thesis, I have used the word “strategic” to represent an approach to addressing environmental issues. The meaning of “strategic” in this context is inspired by two connotations that Nilsson et al. (2005) suggest are implied by the word in their paper on Strategic Environmental Assessment methodology (SEA). The first connotation is that the results of strategic measures will have long-range implications on society in time and space. The second connotation emphasizes an upstream focus, which means that strategic environmental considerations should be taken early to make way for new directions towards sustainability (ibid.).

Systems analysis is an approach that studies complex problems present in society by applying scientific methods and knowledge (Miser and Quade, 1985). Furthermore, the analysis is often used a basis for decision-making. It is difficult to try to define environmental systems analysis but a definition that is close to the view used in this thesis is presented below:

Environmental Systems Analysis treats analysis and assessment of the interaction between anthropogenic (human-made) systems and their environment(s). It aims at providing a basis for decisions and planning for a more sustainable behaviour at an individual, organizational and societal level. (Moberg, 2006)

There are two environmental system analysis methods which are more connected to this thesis than others, namely energy analysis and life-cycle assessment.

Energy analysis is a concept describing the use of energy as an indicator for analyzing societies' impacts on economic or ecological systems. Much of the modern use of energy analysis is inspired by the work of H. T. Odum (cf. 1971, 1994) which introduced energy analysis of the society through the calculation of total energy cost for production. These analyses use the strong impact energy use has on societies' economic and resource flows and thus uses energy use as an indicator of resource activities (cf. Herendeen, 2004). Energy analysis means adding up all energy that directly or indirectly is needed to produce a good or service (ibid.). Hence with today's nomenclature it can be said to include a life-cycle perspective. During the 1970s and '80s many large studies on energy use were carried out in order to

answer for instance how much resource use was involved, how technological change would affect resource use and where there were possibilities to implement energy-saving activities (cf. Johansson & Lönnroth, 1975). Of particular interest to this thesis are some studies on transport systems (cf. Kordi et al., 1979; Kahn, 1980; Boyle, 1984). However, in these studies the focus is on energy efficiency and although this is very much connected to environmental pressures the direct implications for environmental issues are not focused on. Notwithstanding, they form an interesting basis of departure for this thesis. A further discussion on energy indicators is presented in chapter 2.4.1.

Parallel to the introduction of energy analysis as a method for ecological measures in the 1970s, another method was being developed, namely Life-Cycle Assessment (LCA). It has many similarities with energy analysis in that it focuses on all the different production steps of a product or service. However, it has a bigger scope in that it aims at directly quantifying the environmental consequences from a product's life-cycle from cradle to grave (cf. Guinée, 2001). With this larger scope, an issue with usability is introduced which will be discussed further in chapters 2.2 and 2.4. The assessment is standardized in the ISO 14040-series (ISO, 1997; 1998; 2000a; 2000b). The assessment is performed in four phases: definition of goal and scope; inventory analysis; impact assessment; and finally interpretation of the results (cf. Guinée). In this thesis, three of the phases are performed in the use of a simplified LCA concentrating on energy use divided into renewable and non-renewable energy sources or energy use with accompanying CO₂ emissions. However, the impact assessment phase is not discussed.

These concepts form the basis of my viewpoint of the issues behind this thesis. IE is useful as a vision but the concept also includes tools and methods which are touched upon later in this chapter. LCM and ESCM give insights into the organizational changes that are needed in order to incorporate life-cycle considerations. The scoping method proposed in this thesis could easily fit into all of these concepts. Furthermore, environmental management is a concept of the context in which the scoping approach should be used in order for it to be effective. In order to broaden the scope of both the infrastructure manager and the transport research there is a need to use environmental systems analysis to form a basis for decision-making and incorporate life-cycle considerations. In this thesis a form of energy analysis is used, but it also uses elements from LCA since it specifies more than just

total energy used in the system in order to give more guidance on the environmental pressures from the material use.

2.1.1 The DPSIR framework

In this thesis and its appended papers, the DPSIR acronym has been chosen for the labelling and positioning of the research. The concept is used by the European Environment Agency, and the acronym stands for Drivers, Pressure, State, Impact and Response, as seen in Figure 2 (EEA, 1999).

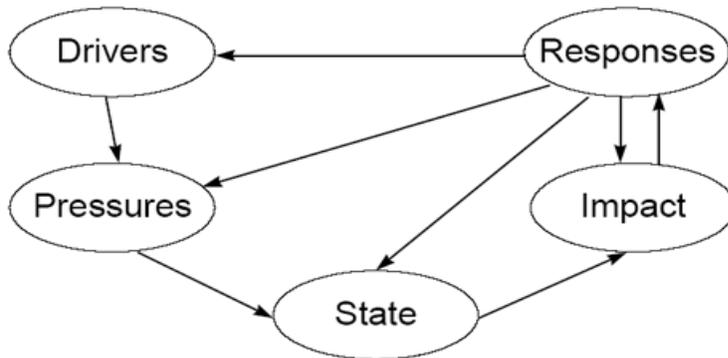


Figure 2: *The DPSIR framework for reporting on environmental issues.*

Drivers in society exert pressures on the environment, which in turn leads to a change in the state of the environment. This change in the environment causes an impact on the earth; examples include the decrease of biodiversity or impacts on human health (ibid.). With this in mind, the research described in this thesis focuses on the pressures that Banverket is placing on the environment through its use of materials. Some parts of this research also address what responses can be made to decrease these pressures.

2.2 Life-cycle considerations in organizations

The environmental pressures in today's society can to a large degree be attributed to flows of material and energy (Ayers, 1994). Furthermore, for manufacturing companies these flows are to a large part connected to products (cf. Berkhout, 1998). It is not hard to extend that to other businesses and organizations that handle large volumes of materials such as infrastructure managers and building companies. However, organizations often do not have the knowledge and tools to deal with these environmental pressures, since it is common to direct environmental management efforts on the specific organization or a specific site and thus these often lack a life-cycle perspective (cf. Klinkers et al., 1999; van Berkel et al., 1999;

Ammenberg & Sundin, 2005). Even if the actors in an organization have the knowledge, there is also a question about the individual capacity to influence the environmental management of the organization.

Heiskanen (2002) put forward that there are indications that life-cycle assessment activities often only involve limited amounts of corporate functions, typically environmental staff, and thus integration in the organization is lacking. Furthermore, the activities are used as an experiment in framing decisions rather than actually solving a specific problem (*ibid.*). Sinding (2000) argues that an organization needs to break its traditional intra-organizational environmental management and engage in a more inter-organizational form of environmental management instead which incorporates for instance life-cycle-oriented management and industrial ecology.

2.3 Scoping environmental pressure

In the initial stage of the environmental management of an organization, decisions are faced regarding prioritizing between different environmental aspects (Ammenberg, 2003). This process should be preceded by an environmental review, for instance in the initial stage of the implementation of standardized EMS's (cf. ISO, 1996). When dealing with organizations' handling of chemicals and toxic substances, this scoping often involves the use of lists or checklists including especially harmful substances. These lists are often translated from specific governing laws. However, environmental pressures related to systems properties such as energy and material use are more difficult to cover, since these pressures are often complex and span different problem areas ranging from local to global. In this thesis, an approach useful for an initial scoping of the environmental pressures from material use within an organization is presented. The approach could be applied, together with other instruments for scoping, in for instance the environmental review of an EMS or in the initial stages of an Environmental Impact Assessment.

In the field of EIAs, scoping is a common initial process to identify the possible environmental impacts of a project (Jones, 1999). However, EIAs seldom incorporate a life-cycle perspective, but instead often only study site-specific environmental impacts (Bruhn-Tysk & Eklund, 2000; Tukker, 2000). Hence, there is a need for an approach which integrates the life-cycle perspective into EIAs in order to expand these assessments into an even more useful process.

2.4 Environmental indicators in environmental management

Indicators are often used to try to simplify complex reality into something that we can comprehend and base decisions on. A decision that has environmental consequences should preferably be based on holistic information. This implies that vast amounts of data need to be collected, interpreted and prioritized. Thus, there is a risk for what Hertwich et al. (1997) call an “analytical paralysis”, i.e. that the collection of data for the environmental impact evaluation is outside the limits of what can be done within the available budget or time-frame. Following the time-consuming process of collecting all the relevant data for such a holistic view, the huge amount of data could mean that the decision-makers face an information overload. According to Speier (1998), information overload in decision-making can be detrimental to the decision performance, and could also lead to a reduction in confidence in the decision. However, she further suggests that there is a risk in using aggregated data, and that detailed data results in more accurate decisions (*ibid.*). This suggests a complicated balancing act between, on the one hand, having too much information which can lead to information overload, and on the other hand, having too little information which can lead to inaccurate decisions. In some cases, such as for decisions made based on a small set of or narrowly conceived data, there might be a risk of so-called problem shifting. Available data could imply a certain decision which could lead to unwanted and unforeseen side effects, which in this case could be an environmental problem arising in another time or space (Raadschelders, et al., 2003). Furthermore, Bengtsson (2002) suggests that there is a link between understanding and interpreting results and the individual involvement in using a tool or method. If a person is actively involved in the making of the environmental systems analysis it may make the information overload easier to overcome (*cf.* Bengtsson, 2002).

Vogtländer (2002) and Speier (1998) state that it appears that decision-makers prefer using aggregated data or indicators, but the latter also states that those that use more detailed data are more confident in their decisions (*ibid.*). Furthermore, life-cycle assessment with less information but with relatively high accuracy would improve the applicability of the analysis greatly (Ong et al. 1999; O’Shea, 2002; Sun et al., 2004). Hunkeler et al. (2003) discuss the need for a tool to be developed in integration with the way decisions are made which according to them will result in management tools which will help to simplify complex interactions.

2.4.1 Energy indicators

In the building, energy and transport sectors it is common to use different kinds of energy indicators as a way to depict the environmental pressures generated within these systems (Alcorn & Baird, 1996; Cole & Kernan, 1996; Suzuki & Oka, 1998; Kloft & Wörner, 1999; Thormark, 2000; Roth & Eklund, 2000b; Gao et al., 2001; Johnstone, 2001; Korhonen, 2002; Federici et al., 2003; Scheuer et al., 2003). These indicators are often expressed as “embodied energy” or “primary energy” use. Embodied energy refers to the amount of energy embodied in a product or service as a result of, for instance, mining through enrichment, transporting, processing and production of a product (Alcorn, 1998; Fay et al., 2000). In contrast, primary energy incorporates all the use of energy carriers with the inclusion of all the losses incurred by the delivery of those energy carriers (Boonekamp, 2003). However, primary energy use is often incorporated when calculating embodied energy (Fay et al., 2000). There is another term which seems identical to embodied energy, which is cumulative energy demand (CED). According to Huijbregts et al. (2006), CED of a product includes the direct and indirect energy use throughout the life cycle. Another energy indicator is exergy, which Connelly and Koshland (1996) define as the quantification of “the amount of work a unit of energy can perform relative to a thermodynamic ground state”. The energy indicator is useful, since the data are easily obtained for single processes as well as in aggregated forms, and several environmentally important impacts are linked to energy use (Rebitzer et al, 2004).

The term “material-related energy use” is used in this thesis as an indicator for the environmental pressures from the studied material use. This is used instead of embodied energy, primary energy or exergy, primarily for ease of use and clarity. Since the results will be communicated to several different actors outside the academic world as well, it is preferable that the results be as self explanatory as possible. Exergy is an environmental indicator mainly used by the scientific community and would require a great deal of explanation and education in order to be useful in this case. While the term “material-related energy use” is in essence the same as embodied energy with the primary energy use incorporated, it was felt that the inclusion of “material-related” would send the right messages to the recipient of the indicator about what it includes if set in contrast to for example energy use for operation.

2.5 Transport research regarding environmental aspects from material use

There have been numerous studies on the environmental aspects of transports. However, the bulk of these studies focus on the operation phase while omitting environmental aspects from building and maintaining the infrastructure. Smith (2003) states that much focus in the research has concerned noise levels and vibration from transports. According to Bouwman and Moll (2002), research studies with a holistic view involving a life-cycle perspective are rare. Instead, the research often focuses on the direct use of energy or emissions from the different transport modes. In order to get a broader perspective for environmental analysis of transport systems, Bouwman and Moll (*ibid.*), Lenzen (1999) and Maibach et al. (1997) suggest that indirect environmental aspects such as the use and maintenance of infrastructure need to be included in these analyses in order to be more representative of the overall environmental pressures from transports. Uppenberg et al. (2003) made a study regarding what is needed to get an environmental declaration of the infrastructure of the transport systems. They stress that a systems approach is needed when analyzing the transport sector's environmental pressures and that there is a need to include the infrastructure in this analysis (*ibid.*). Jonsson (2005) suggests that there have been many environmental assessments of individual products in the transport systems, but there is a need for a larger systematic view.

However, as mentioned earlier in the chapter regarding positioning of the thesis (chapter 2.1), energy analysis of the indirect energy use of transport systems was carried out during the 1970s and early 1980s (cf. Kordi et al., 1979; Kahn, 1980; Boyle, 1984). These indicate the importance of the infrastructure which also leads to the question of how these energy uses influence the environmental pressures from the transport sectors.

Examples of the exclusion of the environmental pressures from building and maintaining infrastructure can be taken from the EIA field. Dom (1999) describes what aspects should be included in an EIA of road and rail infrastructure and these include only site-specific environmental pressures and omit the pressures occurring in the production of the infrastructure materials. This can be attributed to the aforementioned tradition of EIA being site specific and geographically limited (see section 2.3).

In a book concerning “The Environmental Impacts of Railways” the impacts from equipment is mentioned in one short paragraph which claims that

conserving energy resources for raw material extraction can only be influenced by fiscal or legislative controls (cf. Carpenter, 1994). In a special issue of “Journal of Rail and Rapid Transport”² regarding the rail system and the environment there is one article concerning LCA of ties but no systematic analysis of the total contribution of the infrastructure is included.

The research behind this thesis addresses the importance of the rail infrastructure to the overall environmental pressures generated by the railway system, since this is viewed here as a neglected research area.

2.6 Points of departure

The theoretical foundation is important in understanding the point of departure for this thesis. Using another scientific background, the approach and methods would differ from the ones chosen here in order to study the questions in the aims of this research.

My points of departure can be summarized as follows:

- Methods and tools available for environmental management seldom introduce life-cycle considerations that are truly incorporated in the organization. (chapter 2.2-3)
- The change from “end-of-pipe” solutions to strategic and preventive solutions makes it interesting to focus on the inflow of materials to organizations, as this means that problems occurring in a wider system and at the outflow end can be decreased. (chapter 2.1)
- When using environmental indicators, simplification and aggregation of information can be valuable, but should maintain environmental relevance. (chapter 2.4)
- To get a broader system perspective in the environmental assessment of the transport sectors, indirect environmental pressures from upstream production of infrastructure products needs to be included. (chapter 2.7)

²Journal of Rail and Rapid Transport. (2003), Proceedings Part F, Proceedings of the Institution of Mechanical Engineers. 2003, Vol 217, No F4. ISSN: 0954-4097

- In developing a method, it is important to consider the needs of the intended user of the methods, since this makes it easier for the user to interpret the results. (chapter 2.4)

3 Method

This section outlines the research process behind this thesis and further discusses methods and methodological issues pertaining to the research.

3.1 The research process

This research began as a pre-study to investigate how material flow analysis could be used in organizations such as Banverket. The pre-study focused on making a material flow chart for copper use in the Swedish railway infrastructure. Furthermore, an initial discussion was held with the aid of an expert panel in which five materials - copper, aluminium, steel/iron, concrete and ballast materials - were selected for further study based on their use and material-related energy intensity. The pre-study sparked interesting discussions and gave representatives from Banverket some new insights.

The author's research questions had by then started to shift into what improvement measures Banverket could take regarding their material use. The questions posed by Banverket included which products were the most important to focus on and how their material use could be improved from an environmental point of view. From the discussion with Banverket, it became apparent that the organization knew quite a lot about toxic substances in their products, since they had been working in that field for some time. For instance, Banverket has a group of experts that meet and discuss the introduction of new chemical substances into their organization.

In contrast to the management of chemicals, there was a lack of knowledge in the organization regarding resource aspects and which upstream environmental pressures could be attributed to the products Banverket uses. To address these questions, it was decided to scope the environmental pressures from Banverket's use of materials by screening the products used in the infrastructure, in search of environmental hot spots. This led me to make a material inventory of a railway building project (Paper II). The studied materials also came to include zinc since I had indications that there were many galvanized railway articles involved in the railway project. In addition to making the inventory, an analysis of the material-related energy use of the project was carried out as a proxy of the environmental pressure for the building project. This inventory yielded a couple of new questions which I felt needed further investigation. First, what importance does the environmental pressure of the infrastructure have for the overall

environmental performance of the railway transport mode? Second, what environmental relevance does the indicator material-related energy use have to the overall environmental pressure? In order to analyse the first question, I initiated a study of the energy use and CO₂ emissions of the railway and road transport modes to see how much the infrastructure contributed to the overall environmental pressures (Paper I). The use of an energy indicator as an environmental indicator was found in many other studies but it was rarely critically discussed why it was used and to what extent it was reflective of the real environmental pressures. Subsequently, there was a need to assess how an energy indicator reflects environmental pressures for different environmental impact categories (Paper III).

In the research discussed in Paper II there is a hypothetical argument about the importance of transport from the producer to the project site. Since that hypothetical exercise found that these transports could be of utmost importance, there was a need for further investigations. Thus a study of three railway projects was undertaken and the transport share of the total energy use was in focus (Paper IV). These were done to further test the robustness of the scoping approach developed in the first study leading to Paper II.

Still I felt that there was a need to address some concerns about how life-cycle considerations were dealt with within an organization and in this case Banverket in particular. Thus an interview study with representatives from different Banverket units was undertaken to find what preconditions existed for introducing life-cycle considerations into the organization (Paper V). The informants were key persons in the material supply process and the interviews aimed to find possibilities for, and hindrances to, implementing life-cycle considerations. This led to a greater understanding of how organizations work with environmental issues and to some extent what is felt to be needed to facilitate a more efficient environmental management.

3.2 Building projects studied (Paper II and Paper IV)

The building project studied in Paper II is a newly built railway in the proximity of Stockholm, between Kungsängen and Kalhäll (Table 1). This project was chosen since it had been used for a project regarding a revision of logistics to projects and thus the article list had been reviewed and fully computerized. All articles used in the project were new. This was important in order to ascertain that it was a complete article list that was screened. However, to get a complete picture of how the material use for a railway is composed, ballast materials and concrete foundations, which are not

classified as railway-specific, were also included in the study. The distance is 6.9 kilometers long and includes a couple of tunnels and bridges. However, in this case study, the investigation was limited to railway-specific articles, ballast materials and concrete foundations for power-wire posts. Therefore, tunnels and bridges are not accounted for in the study, since they are specific to each project, and the aim was to obtain a general picture of the railway.

The studied building projects in Paper IV are summarized in Table 1. The first stretch between Stockholm South and Årstaberget (stretch I) is a new multi-track with a large bridge. The rail and tie use is calculated from the whole stretch which is about 1.7 kilometres while the ballast use is calculated from a 0.9 km stretch excluding the bridge. The second stretch is a rearmament project of the track between Vännäs and Bastuträsk (stretch II) which is 110 kilometres. Finally, the third stretch is a new double track between Öxnered and Trollhättan (stretch III) which is 7.8 kilometres including a tunnel of 3.5 kilometres.

There are significant differences between the three studied stretches (from here on called stretch I to stretch III). The main differences regard the ballast handling which is due both to geology and the prior history of the stretch. The distance to the ballast supplier is more than six times larger for stretch III than for stretch I.

Table 1: *Characteristics of the studied stretches in Paper II and IV.*

Stretch	Used in paper	Length	Type of project
Stretch I	Paper IV	Including bridge: 1.7 km* Excluding bridge: 0.9 km	New multi-track (varying no. of tracks)
Stretch II	Paper IV	110 km	Rearmament
Stretch III	Paper IV	Including tunnel: 7.8 km* Excluding tunnel: 4.3 km	New double track
Kungsängen-Kalhäll	Paper II	Including tunnels and bridges: 6.9 km*	New double track

* The material-related energy use for the tunnels and bridges was not included in the studies. However, the full distances were used to get the amount of rails and railway ties used in the projects.

3.3 Development of the scoping method

In the development of the scoping method I have used the term *articles* for each individual piece of railway equipment and then used the term *product* in order to group these articles. For instance, there are several rail articles that constitute the rail product. Furthermore, each of these articles consists of

one or more materials, but I will refer to an article's *material* as the major material in the article. This choice was made since the bulk of the railway articles are made up of one or at most two different materials, i.e. ties, rails, posts, ballast, etc. The method for scoping environmental pressure, by screening products, used in this thesis follows an outline of starting from determining material use per article, determining the weight per article, then determining the total weight of article in an actual building project, screening relevant products based on screening criteria, and finally scoping the environmental pressures by determining material-related energy use for the case (Figure 3).

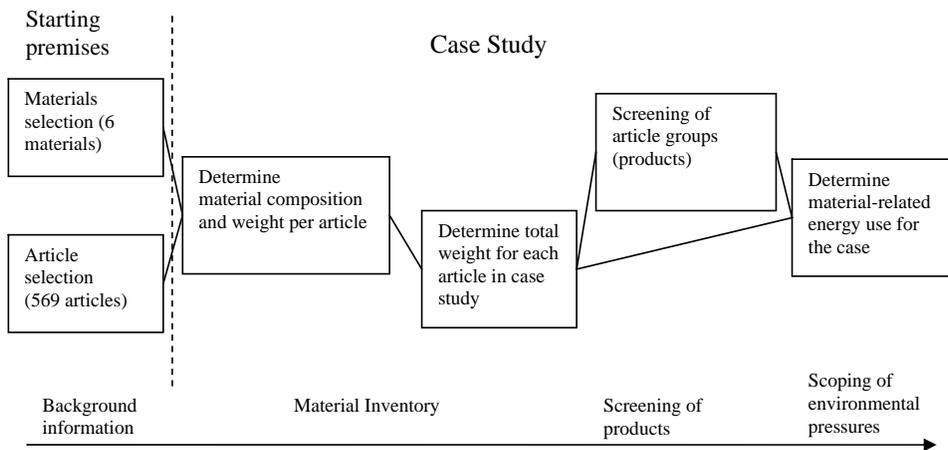


Figure 3: The outline of the scoping method, detailing the steps needed to make the initial scoping of environmental pressures.

An inventory of Banverket's products could potentially include a large number of materials, so among our first priorities was decreasing the number of materials to study. This was based on two different premises. First, I had a discussion with an expert panel of representatives from Banverket. This discussion led to a list of materials which, from the expert's knowledge, were estimated to contribute to a large part of the railway infrastructure's material use. The second premise was that the materials studied were chosen keeping in mind their energy use in a life-cycle perspective. With these two premises in mind the screening of the products focused on articles consisting of the following six materials (in alphabetical order):

Aluminium
Concrete
Copper
Crushed rock
Steel/iron
Zinc

In order to make the screening of the products I used weight criteria which a product grouping would have to meet to be studied further. However, since some materials are more energy intensive than others, a smaller weight is needed to add significantly to the overall material energy use. Thus, for copper and aluminium the criteria for inclusion in the screening were lower than for the other materials. The weight criteria for the screening of railway specific products were chosen to be:

- Concrete and steel/iron articles: total weight (weight per product * number of units per kilometer) of the product grouping is above 500 kg/km
- Copper and aluminium articles: total of the product grouping is above 50 kg/km

Zinc was estimated at 7% of the amount of galvanized steel. It is also important to note that it is product groupings that are screened. This means that some articles, for instance copper cables, that are sometimes used individually in small amounts, become a rather large factor in the copper use for the entire railway project.

3.3.1 Material-related energy use

I have used “material-related energy use” as an indicator for environmental pressures from material use. This indicator is in effect the embodied energy of the materials that is calculated with the primary energy use needed for the different extraction and production processes for the different materials. However, it is only the extraction and refinement phases that are included in the analysis (see Figure 4). These two phases are used as an estimation of what the environmental pressures can be for a system that includes the phases up to the construction of the infrastructure. Another word that is used in this thesis is cradle-to-gate, which means that cradle could be substituted with mining and gate with the last process step in the refinement phase. Thus the production of the final product is excluded. Material life-cycle databases usually incorporate the first two phases, and thereby it will be easy for

Banverket to redo the analysis. Furthermore, it also meant that it satisfied the need for an easy to use approach. Studies have shown that it is common that the highest environmental pressures arise in the early stages of production (cf. Clift & Wright, 2000). Guggemos and Horvath (2005) found that for both steel- and concrete-framed buildings, the materials and manufacturing phase had very high energy use compared with the construction and end-of-life phase and when the operation phase was excluded. In a related study of Banverket, the authors found that for nine railway articles studied, the environmental pressures from material extraction and refinement contribute to about 50-90% of the environmental pressures up to the construction phase (Eklund & Svensson, 2003). The lower percentage is attributed to two articles, namely contact wire posts for which the galvanization adds significant energy use, and traffic signs which go through an energy demanding hot rolling (ibid.). For the other products, the material extraction and refinement were close to 90% (ibid.). Thus, to get an initial time-efficient scoping of environmental pressures this choice of indicator is appropriate. After this initial scoping, further analysis can be made of the highlighted environmental hot-spots through an enlargement in scope and studied indicators. It is also of note that the articles studied are generally non-complex and of homogenous materials, which means that the production phase consists of few assembly and shaping processes.

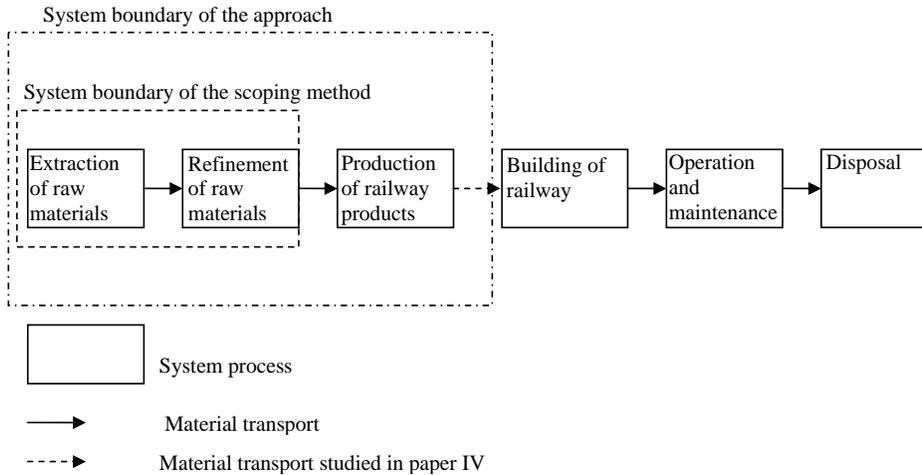


Figure 4: Describes which processes and transports are included in the “material-related energy use” indicator as well as describes that the indicator is used as an estimate of the environmental pressures from a larger system. The dashed arrow shows which transport is studied in Paper IV.

The term “material-related energy use” is primarily used in Paper II and Paper IV but also has a role in Paper I since it is part of the total energy used in the transport systems studied in the latter paper.

In Paper I, the authors used energy use and CO₂ emissions to highlight one of the more politically discussed environmental issues of the transport sector, namely the climate change problem. This was done by calculation of the emissions caused by the energy use for the transports, refining, production and maintenance of the infrastructure products. Furthermore, energy use for building of the infrastructure as well as the operation of the infrastructure and the rolling stock was included in the study behind Paper I.

3.3.2 Studying the approach’s robustness

When performing an environmental analysis it is always important that the method or approach used be transparent, and that the results can be validated to show the robustness of the approach. This is valid for all kinds of system analysis (cf. Quade, 1995). It is essential to evaluate the impact on the results of choices made in defining the system boundaries and characteristics (cf. Guinée, 2001).

Rebitzer et al. (2004) specifies five criteria that should be met by simplified methods, which in their context means simplified life-cycle assessment (LCA). However, I feel that the criteria is relevant even for other types of simplified assessment methods.

- a) Relevance: Is the method compatible with the intended users' intentions?
- b) Validity: The simplified method should give the same rankings/insights as a more detailed method.
- c) Compatibility: Is it possible to integrate the method into existing databases and tools used by the intended user?
- d) Reproducibility: Another user should be able to reach the same ranking results if they use the method.
- e) Transparency: It should be easy to understand the calculations behind the result and also to find the most relevant environmental issues and processes.

In Papers II, III and IV, sensitivity analysis and/or scenarios have been used to validate the model used. The aims of these analyses were to highlight the importance of choices made and analyze what impact they had on the final outcome of the analysis. In a sense, Paper III can be seen as an extended validation of the other papers, since it deals with the relevance of the energy indicator used in Papers II and IV. Paper I and Paper V are excluded from this section since they do not deal specifically with the scoping method. However the robustness of the analysis used in Paper I is discussed in that paper.

3.4 Using case studies

The aim of this thesis is carried out through the use of a study object, which is Banverket in its role as responsible authority for the Swedish railway. In Paper II and Paper IV, the authors have used building projects as case studies for the material inventory. These cases could be seen as being on two different levels, where Banverket is the higher level case for this thesis and the building projects are used in the individual papers as case studies to give insights into the higher level case. A major incentive for using case studies is that they provide empirical data that can be used to test theories and study how different methods and approaches can be used in real situations. However, there is also a caveat concerning which of this empirical data can be generalised and which are specific for the case study (cf. Stake, 1994). Stake identifies three different forms of case studies: intrinsic case study,

instrumental case study and collective case study (ibid.). The first is carried out with the object of understanding the particular case better, while the second is done to strengthen or weaken an issue or theory. The last kind denotes instrumental studies that are extended to several cases. The author of this thesis views this representation to be correct, but rather than having strict boundaries between the different forms, sees them as a continuum. A study can be intrinsic in some parts but instrumental in others. Intrinsic in this thesis refers to those parts where the results are more descriptive and with limited generalisation abilities.

3.5 General applicability of the results

In this chapter, the generalisation aspects of the results from the different papers are presented.

Paper I is a comparison of two Swedish land transport systems and thus is mostly of national concern. However, some of the results are of importance for comparing road and rail systems with similar technology. This paper synthesizes the results from several case studies and analyses to new information making it partly a case study. The studied cases are in this context models of road and rail transport systems.

The results from Paper II are in a way both instrumental and intrinsic. The instrumental part deals with the approach used for making the material inventory. Experiences of using this approach could be generalised to other organizations with similar types of material use, such as infrastructure owners in the building or transport sector. The organizations that may benefit from the suggested scoping approach should deal mainly with management of non-complex products, preferably consisting of few materials. However, the specific results from the study of Banverket's material use are more intrinsic by nature. These results could be generalised to similar rail systems using the same technology as Sweden, e.g. using contact wires in a catenary style.

Paper III generalises about the use of energy as an environmental indicator. The paper deals with energy systems that are predominately fossil based but also comments on how the indicator is affected by other systems built up by other energy carriers.

The fourth paper is a collective case study and has both intrinsic and instrumental value. The instrumental value is that for organizations dealing

with large volumes of materials it can be interesting to see how much transports is needed to offset the environmental pressures from material use.

The interview study behind Paper V can also be said to have both intrinsic and instrumental value. It is quite intrinsic in that it gives insight only into Banverket's organizations. However, it can give knowledge about organizations that can be useful for other scientists as well as other organizations about the kinds of problems and challenges presented by introducing life-cycle considerations.

3.6 Summary of the contributions of the appended papers and the methods used

In this section I will discuss briefly the methods used in the appended papers. For further discussions of these I refer to the individual papers. Table 2 shows a summary of the study objects, main methods and also the main contribution to the thesis aims for each paper

Paper II used an approach in which article weight and energy intensity of its material was combined to screen out the most important articles from an environmental perspective. This environmental perspective focuses on resource issues and upstream environmental pressures from extraction and processing of materials.

Papers I and II both use a quantitative analysis of environmental pressures to address their research questions. The analyses use a cradle-to-gate perspective. In both those papers, the choices of system characteristics are scrutinized by the use of different scenarios and sensitivity analysis.

Paper III begins with a literature review of the use of energy indicators in research and in environmental management. Furthermore, a semi-quantitative analysis of the energy indicators' contribution to a selected set of impact categories is carried out. The authors use literature and databases to either qualitatively or quantitatively estimate this contribution.

In Paper IV an assessment of the materials transport share of the total energy used in three railway projects is analysed. The information about the usage and transports of the studied materials used on the different stretches was analysed to obtain data on energy use that have been used for every material or product. The results from Paper II are used to focus the analyses on the most important products.

For the study in Paper V interviews with employees with different roles and positions in the organization were carried out. The aim was to get a picture of the different actors' roles regarding environmental pressures from products used in Banverket and also their capacity to influence the environmental work regarding the products. The interviews were done using a semi-structured layout with a couple of clearly defined overlaying questions.

Table 2: *Summary of the study objects, main methods and also the main contribution to the thesis aims for each paper*

Paper	Study Objects	Main method	Contribution to thesis
I	Environmental pressure from the railway and road sector	Quantitative assessment of environmental pressures through use of an energy indicator	Relates the material use to the operation phase and compares it with another system.
II	Material use of a railway building project	Quantitative assessment of environmental pressures through use of an energy indicator	Puts forward an approach for scoping environmental pressure of material use through screening of products
III	Energy indicator as an indicator of environmental pressure	Literature review and a semi-quantative assessment of energy use's share in environmental impact categories	Explores the environmental relevance of the used energy indicator
IV	Transports relevance of total environmental pressure in railway building projects	Quantitative assessment of environmental pressures through use of an energy indicator	Discusses the robustness of the suggested scoping approach and discusses the importance of transports in the life-cycle perspective
V	Life-cycle considerations in Banverket's material supply process	Qualitative interviews	Gives an insight in the organization in which the scoping approach is introduced, discusses the possibilities and hindrances to implementing life-cycle considerations

4 Results from appended papers

This chapter is structured to first give an introduction and context to the material use in the railway infrastructure by contrasting it to the operation phase and comparing it to the road transport system (Aim I). After that the scoping method is introduced and tested (Aim II). Finally, an organizational context is presented which will highlight into which organizational setting the approach is introduced (Aim III).

4.1 How does the environmental pressure from material use compare to the operations phase and to other transport systems? (Paper I)

The results from the comparison of the road and rail transport systems highlight many interesting issues. The energy use attributed to the systems by building, maintaining and using the infrastructure, combined with the energy use from the transportation, show that the rail systems' infrastructure uses more energy than their road equivalents (Figure 5). This is consistent with results from similar research done in Switzerland and Australia (Lenzen, 1999; Maibach et al., 1999). It is also notable that the energy use for infrastructure is almost entirely from non-renewable energy sources. Furthermore, due to the higher load factors of buses, the energy use for them is lower than their rail counterparts. However, buses use energy from non-renewable energy carriers, while Swedish electrified passenger trains use mainly energy from renewable sources. The latter can be explained by the high amount of electricity from hydro power for the Swedish electrified trains. The diesel passenger trains, on the other hand, use more non-renewable energy for their traffic part than the buses do. Cars are by far the most energy-consuming vehicles, which was to be expected due to their, in this context, low load factor. For the freight transports, the train transports use less energy compared to trucks.

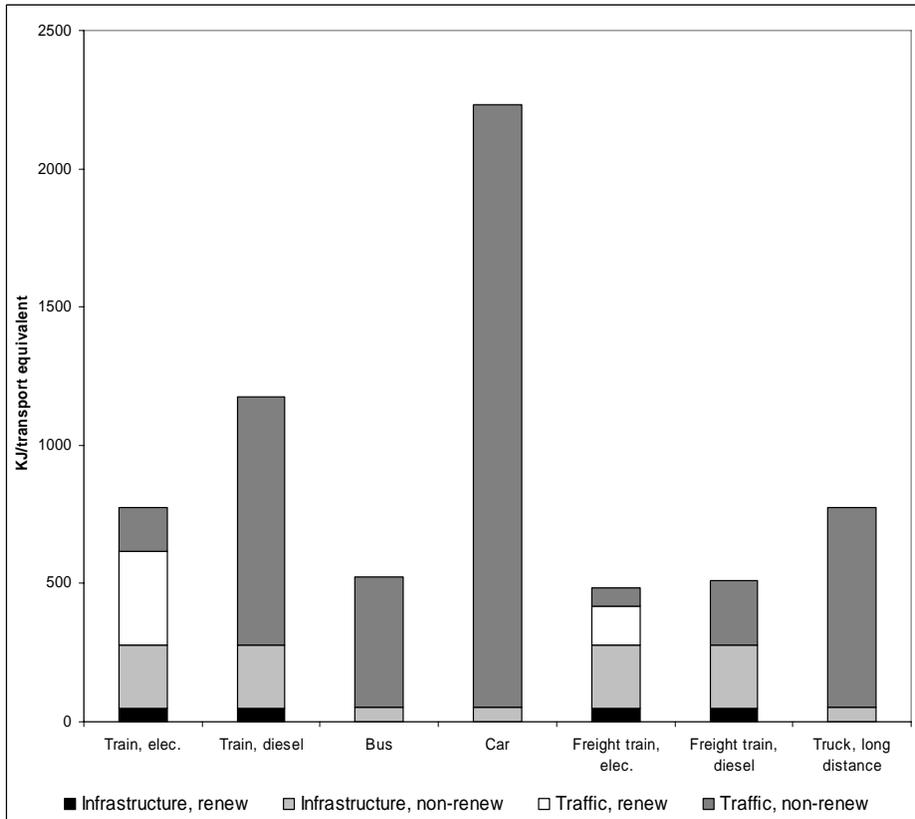


Figure 5: Renewable and non-renewable energy use distributed between infrastructure and traffic for different road and rail vehicles. (Paper I)

While the differences between the road and rail systems seem small, in the case of energy use they become larger if they are converted into corresponding CO₂ emissions (Figure 6). For electrified passenger trains, the emissions related to the infrastructure are higher than emissions from traffic. It is also evident that the use of non-renewable energy generates a larger difference between CO₂ emissions for electrified passenger trains and buses. For the electrified freight train, the high load factor combined with the use of mostly renewable energy for the traffic part leads to the share of emissions from the infrastructure becoming significant.

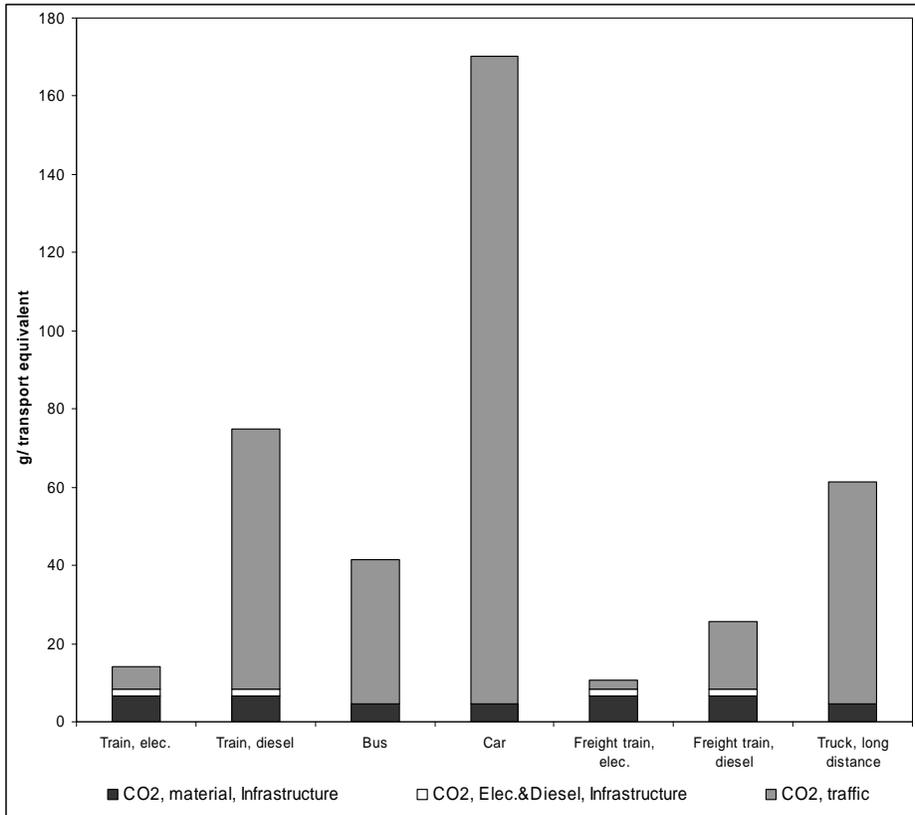


Figure 6: *CO₂ emissions distributed between infrastructure and traffic. CO₂ emissions from electricity and diesel used for maintaining the infrastructure are separated from CO₂ emissions from material-related energy use. (Paper I)*

Furthermore, the study included an analysis of the importance of some assumptions used in the analysis. The factors which were further analysed were load factor, road lighting, choice of energy system for electricity production and end-of-life treatment of the products.

Two scenarios were made to study the importance of the load factor: one with increased load factor for the railway transport to equal the average EU15 load factor, and one with decreased load factor. Even if the load factor for the rail vehicles is decreased or increased by almost 50%, there is no change in order between the vehicles when it comes to CO₂ emissions. The

load factor is still a very important aspect when analyzing transport systems which will be further discussed later in this thesis.

According to Stripple (2001), the operation phase of the road infrastructure is dominated by road lights. However, we have assumed that 5% of the road has lights, since we argue that for long-distance transports the roads would mainly be outside urban areas, roads which in Sweden seldom use road lighting. If however, we change this assumption to 25% lit road we get a noticeable increase in energy use. Since energy use for the traffic phase of the road system is high compared to energy use by infrastructure, the impact of a higher degree of road lighting is small. However, for individual stretches, such as close to urban areas, road lighting can possibly be an important factor.

Changing the way in which electricity is produced affects the outcome of the results for CO₂ emissions for passenger transports if a system almost entirely based on fossil-based fuels is used (CENTREL mix). However, even with this big change in electricity production the electrified freight train causes fewer CO₂ emissions compared to trucks. Using a more moderate electricity mix (NORDEL) yields the same ranging order as the base results.

If end-of-life treatment for rails is included in the analysis through allocation of energy use by reuse on regional tracks, CO₂ emissions could be decreased by almost 20%. This would make CO₂ emissions from railway infrastructure only slightly higher than its road equivalent. Recycling is not included or assessed in this study, partly due to the fact that after use they leave the domains of influence for the actors of the transport systems. Rails are recycled to a product with lower quality demands after maybe 150 years use on mainline track and regional tracks, which in turn leads to complex allocation problems. However, since the railway infrastructure is more dependent on steel products than the road equivalent it would probably benefit more from an inclusion of recycling since the other materials do not have the same environmental gains from recycling.

4.2 Scoping of environmental pressure from material use in a large organization (Paper II, Paper III and Paper IV)

The material inventory of a rail building project involved 569 different railway articles (Paper II). These ranged from small screws and bolts to rails, ties and posts. The screening of the articles was done to make it possible for Banverket to scope the environmental pressures from the articles. The bulk

of the articles consisted of non-complex articles composed of one or a few materials. About 98% of the material use depends on 80 articles, which is about 12% of the articles used in the project. For the material categories studied, with the exceptions of zinc and copper, one product constitutes over 90 weight-percentage of the material use for each material (Figure 7). Zinc is slightly different, since it is contingent on the use of steel products as its main use is in galvanized articles. The largest material use of galvanized products can be attributed to contact wire posts, which represent about 35% of the zinc used. For copper, the products that are used in the contact wire system constitute about 65 weight-percentage of the overall copper use. Steel rails, concrete ties, ballast materials from crushed rocks and aluminium cables are the most important products for their respective material. Of the latter products, the first three contribute 99.5 weight-percentage of the building project.

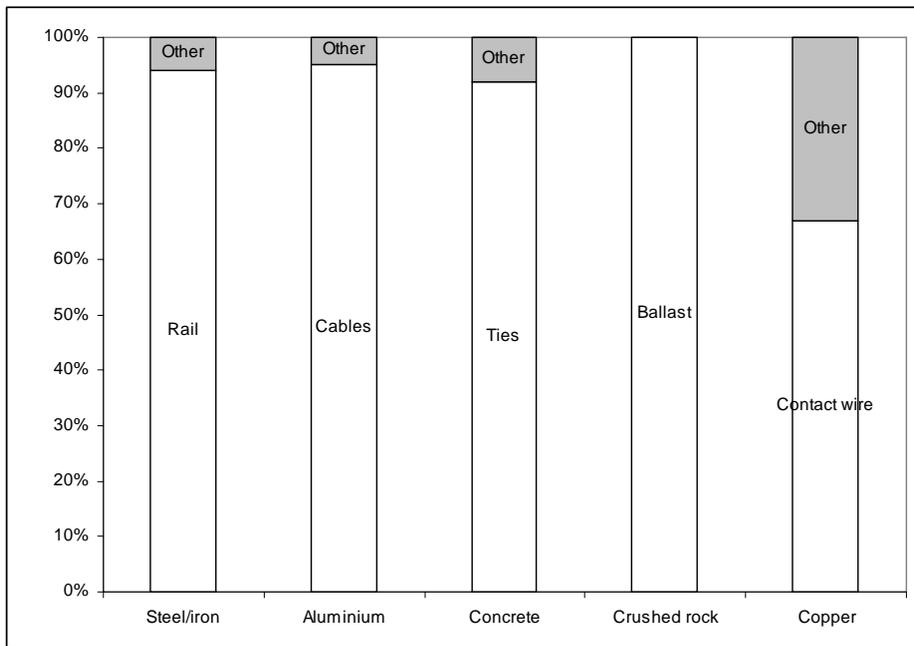


Figure 7: The five studied materials and the share of the material use for the major products in a railway building project. (Paper II)

However, material use itself does not necessarily reflect the environmental pressures from the materials. The overall material use is totally dominated by the bulk material, crushed rock (~94%), while concrete articles (~4%)

and steel/iron articles (~2%) play only a minor role (Figure 8). This ranking order changes if material-related energy use is calculated for the materials and then used for prioritization between the materials. Due to the energy-intensive production of steel, these articles form 77% of the overall material-related energy use, while crushed rock adds up to about 9% by the sheer size of the material use, since it is less energy intensive compared with the other study materials. If we combine the results presented in these two paragraphs, it becomes evident that the use of rails is of utmost importance for the overall material-related energy use.

The material use and material-related energy use is totally dominated by three products: steel rail, concrete ties and ballast materials. These products are non-complex and non-toxic, and the first two are also used similarly in different railway projects. The use of ballast materials is contingent on geology and what type of load the railway will have. Furthermore, all in all about 97% of the total material-related energy use is from non-renewable energy sources.

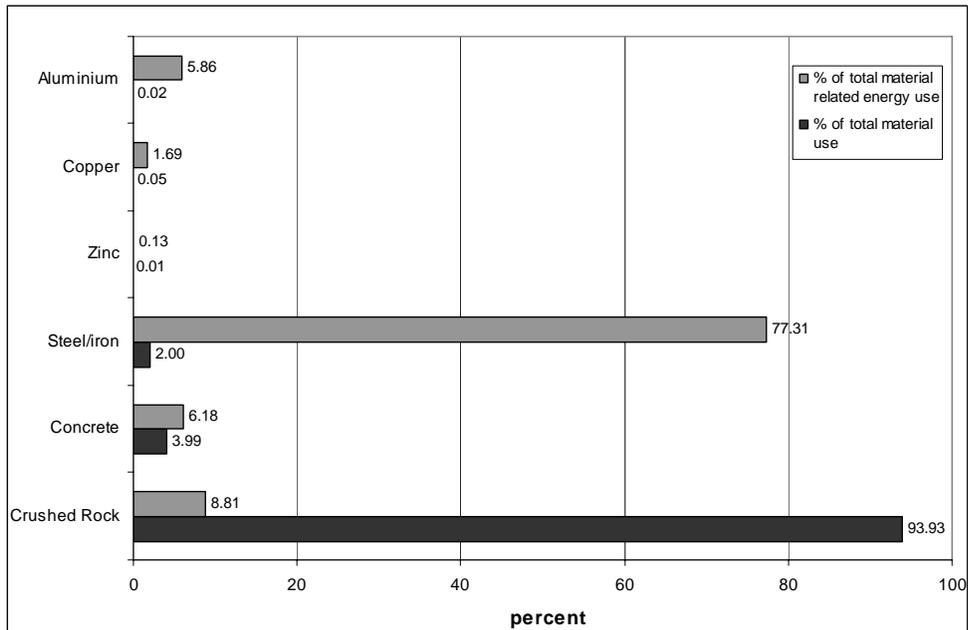


Figure 8: Material use and material-related energy use for the railway building project between Kungsängen-Kalhäll. (Paper II)

Another important part of paper II was to study the impact of the assumptions and choices made when using the approach. The study's authors conducted quantitative and qualitative analyses of the following areas of assumptions and choices:

- Selected materials
- Screened products depiction of the project's environmental pressures
- Simplification of product complexities
- Case representativeness
- Only including cradle-to-gate data
 - transports to project site from factories excluded (this is discussed in further detail in Paper IV)
 - data uncertainties regarding the applicability in this certain case
 - environmental pressures from use and end-of-use is not included
- The environmental relevance of the chosen energy indicator (this is discussed in detail in Paper III)

After the study which was presented in Paper II, two main areas were chosen for further studies in order to go into depth with the approach's robustness. These were the use of the energy indicator and to what extent it could be used as a proxy for environmental pressure (Paper III) and the importance of the materials transports to the site from the supplier (Paper IV).

4.2.1 The environmental relevance of the energy indicator

The use of energy indicators in environmental reviews and analyses are commonly found in environmental management and research dealing with the energy, building and transport sectors. This can most likely be explained by the fact that all of these sectors have large environmental pressures resulting from the use of energy in their respective use phase. However, the environmental relevance of the energy indicator is often not commented on, but rather taken as self-evident. The environmental relevance of the energy indicator is contingent upon in which energy system the studied activities occur. In the context of this article (Paper III), we have tried to assess the relation between, on the one hand, the immediate supply, conversion and use of energy, and on the other hand, environmental impact categories with weak, moderate or strong relations (Table 3). By "immediate" we refer to combustion and other energy conversion processes, mining of energy carriers and handling of by-products and waste. If used in a fossil-based energy system, the indicator to some extent reflects impact categories like climate change, acidification, photo-oxidant formation and toxicity aspects from particles and hazardous chemical flows. The energy indicator does not reflect environmental pressures from toxic emissions very well, which should be noted when analyzing complex products. Thus, it is important to consider environmental pressures not related to energy use, in order to incorporate the most important environmental pressures. The purpose of this consideration is to conclude whether an energy indicator might be sufficient or if complementary indicators are needed. Otherwise, there could be numerous pitfalls, such as problem shifting and the risk of leaving out significant environmental pressures. While communication of a single indicator is powerful, it also implies that the description of the energy indicator needs to be transparent to the receiver, and specifically to address the validity of the results and to highlight what is excluded.

Table 3: 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(/). For details behind the classification the author refer to Paper III. This means that 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. (Paper III)

Impact categories	Services & households	Industry	Transportation	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	○	○	○	○

4.2.2 The environmental importance of materials transports

The importance of the materials transports depend largely on the handling of the ballast materials. We have studied the materials transports for three different railway building projects. If the ballast can be taken from the site or from a quarry close to the project site there is much to be gained (Figure 9a and 9b). Even though the material use is comparable for two of the stretches, the energy use of the ballast materials is dominant in stretch III compared with stretch I. This is mainly due to the long truck transport distances of ballast materials used for stretch III. Since stretch II is a rearmament project, the amounts of ballast materials in this project is not directly comparable with the other stretches, but it still gives an example of the potential for improvement. However, it is notable that the transport-related energy use in this project is higher than for stretch I, despite the fact that the latter is an entirely new railway with larger material use. This depends on the transport distance being about three times as long in stretch II, and that all the material is bought externally, which is not the case in the project for stretch I, where all the sub-ballast is taken from the site. The reason why the energy used for the transports of ballast materials in the project of stretch I is so low compared with stretch III is partly that the sub-ballast is taken from the site and therefore not transported, and mainly that the transport distances are rather short.

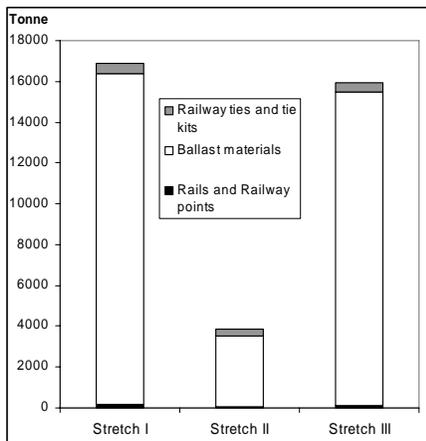


Figure 9a: Comparison of material use calculated per km single railway track. (Paper IV)

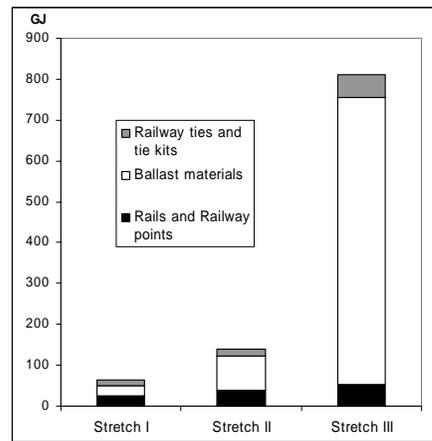


Figure 9b: Comparison of energy used only in the transports of the materials used on the different stretches, calculated per km single railway track. (Paper IV)

As for the share of the materials transport to the total energy use from cradle to project site, these ranged from about 1% for stretch I and close to 13% for stretch III (Figure 10).

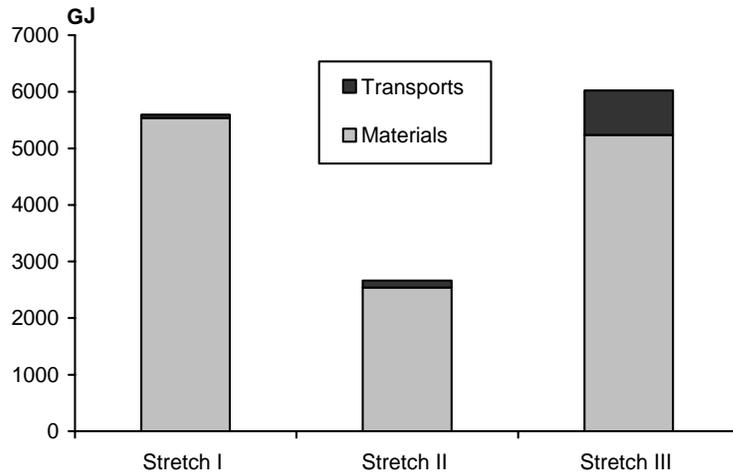


Figure 10: Total energy use for the different stretches, calculated per km single-track and distributed on the categories transports and extraction and refining of materials. (Paper IV)

The share of the materials transport to the total material-related energy use is rather small but in some projects it has the potential to be significant. Thus it is important to investigate how the ballast is handled when making an environmental assessment of a railway stretch.

4.3 What are the possibilities for and hindrances to incorporating life cycle considerations in Banverket? (Paper V)

This aim was analysed through a study on the present practice of one organization's life-cycle considerations of products aimed at identifying opportunities, obstacles and improvement potential, bearing in mind the environmental pressures from these products. This was done through an interview study of key persons in the material supply process of Banverket.

The major influences to environmental aspects of the material supply process seem to be the technical department, which makes the technical specifications of requirements, and the procurement department, which handles the contacts with product suppliers and thus communicates the

environmental requirements. The procurement department and one of the technical departments feel that a great deal of support from top-level management and other departments is needed to help in prioritizing environmental issues. The other technical department feels that they need to do everything themselves since no one else would do it for them. On the other hand, both informants from the technical departments seem to lack a life-cycle perspective on their products while the informants from procurement seem to recognize that there are life-cycle environmental issues but feel that the law on public procurement hinders them from pursuing the issue.

For the maintenance department the issues of reuse and recycling seem to be in focus in regards to environmental requirements. However, the environmental issues from the inflows of new products are referred to the technical department. The environmental department wants to deal with the bigger issues like translating national environmental goals and ideally does not want to function as a support to other departments. From the interview with top-level management it is possible to see that they have visions for environmental management but lack instruments to guide the rest of the organization. The logistics department is one of the few that seems to experience customer demands (although mostly it is internal customers within the organization). The demands were mostly about what different products contained and did not include material-related energy use.

The environmental management of the material supply process seems to be dominated by a focus on hazardous substances and chemicals and only weak links to life-cycle environmental pressures are present. The management of hazardous substances and chemicals seems to be more operative than strategic, since it is more a matter of hindering them from entering the organization rather than working long term and including the thinking in the initial making of the technical specifications. However, the hazardous substance management still has strategic implications since they address the inflow of harmful substances. There seems to be an underlying agreement that Banverket does not set very strong environmental requirements regarding their products. The requirements are mostly lists of prohibited substances and chemicals and some rather vague questions of a more informational nature.

Since most of the environmental requirements used are derived from legal requirements, this could possibly explain why the life-cycle perspective is

left out. There is a difficulty in translating the legal requirements which deal with life-cycle environmental pressures since the latter are often global environmental problems with a rather complex and diffuse picture regarding responsibility and capacity to influence. This is in contrast to legislation regarding toxic emissions and hazardous substances that have more obvious implications as to who is responsible and how organizations are affected by the laws.

The experience of the importance of the environmental management system seems to vary among the informants. However, most of the persons at the headquarters think that their work has not been affected while more operative units seem to think it has a larger influence. Since most of the strategic environmental decisions should come from the different units at the headquarters, this means that these decisions are not incorporated into the environmental management systems.

5 Discussion

The discussion is structured according to the various sub-aims. First the strategic relevance of material use to the railway transport sector is discussed. Secondly, a discussion of the scoping approach is presented in which environmental relevance is discussed as well as the robustness of the approach. Finally, the approach's usefulness in strategic environmental management as well as the preconditions for life-cycle considerations in Banverket are discussed.

5.1 Strategic relevance of life-cycle considerations in the railway transport sector (Aim I)

One strategic dimension of the results presented in this thesis is what the contribution of the infrastructure's environmental pressures could mean for the entire railway sector. If it is assumed that railway transports in Sweden mostly use electricity from hydro and nuclear power, either through "green" electricity or the Swedish average electricity mix, it is obvious that a substantial part of the greenhouse gas emissions from railway transports in Sweden can be attributed to the material-related energy use of the infrastructure. This highlights the importance of the infrastructure to the overall environmental pressure of the railway. Consequently, if for example the road transports were to shift away from fossil fuels, the perceived environmental advantages of the railway would diminish, since findings in this thesis as well as earlier research suggest that railway infrastructure is more energy-intensive than road infrastructure (cf. Kordi, 1979; Lenzen, 1999; Maibach et al, 1999). In contrast, Jonsson (2005) shows results where the road infrastructure seems more energy-intensive. However, our study compares a double-track railway with a 13-meter road whereas Jonsson compares the total railway system with the total road system which are two quite different forms of analysis since the latter would yield a comparably low load factor for the road. Since our study focuses on long-distance travels there are reasons to believe that the road transport load factors are higher than if all road transports are divided across the total road infrastructure (cf. Lenner, 1999). Furthermore, one dimension of this is that currently the railway transports have an environmental advantage in that they are energy efficient and not as reliant on fossil fuels as road transports are. This is an environmentally strategic advantage for the railway compared to road transports which should be of concern for railway organizations who want to increase their share of total transports. This might also imply that railway

organizations should try to minimize their use of fossil fuels in order to keep their relative advantage versus road transport. This advantage could be the basis for the strategic environmental management of the railway organizations, since efficient use of mainly renewable resources leads to potentially higher environmental goodwill. This, in turn, could increase the demand for railway transports, making it a truly strategic environmental issue. Hence, there is a need to continuously improve resource efficiency in the railway sector since it concerns an environmentally strategic dimension.

Another strategic issue is when railways should be used instead of road transports, and vice versa. The rail transport system is often seen as a better environmental choice, but the results in this thesis show that that is not always so. In the Swedish transport system with comparably low rail load factors, diesel passenger trains use more energy and cause more CO₂ emissions than passenger buses. Thus, these results indicate that the diesel passenger trains with low load factors could be exchanged with bus transport based on environmental performance. However, the tracks used by the passenger trains are also used by freight trains, which arguably use less energy compared to long distance trucks. If the passenger trains are taken out of traffic, the freight trains would use infrastructure that is dimensioned for a higher traffic load, and subsequently more of the material-related energy use is allocated to the freight trains. It is of course necessary to go more into detail on load factors when analyzing specific stretches (cf. Kordi et al., 1979). Furthermore, there will always be aspects other than environmental issues, such as social, political and economic factors, governing the decisions regarding the transport systems. For instance, Smith (2003) argues that road transports have a higher degree of accidents compared to rail transports. Furthermore, he goes on to claim that railways' best passenger niches are high-speed transport and high-density commuting (ibid.). These two niches would probably mean high load factors which I believe are an important prerequisite if the railway sector still wants to be perceived as the most environmentally friendly land transport mode.

5.2 The applicability of the scoping approach (Aim II)

The applicability of the approach relies on its robustness. Since Banverket's material use is totally dominated by three products, much of the sensitivity of the approach is contingent on these products' characteristics. The energy indicator used in the approach is best suited for assessing environmental pressures from non-complex and homogenous products, which these products are. Furthermore, studies which use regression analysis have shown

that the energy indicator has a high correlation to many impact categories as is also shown in my research (cf. Huijbregts et al., 2006; cf. Udo de Haes, 2006). However, there was a low correlation between for instance energy use and impacts from land use and toxicity (Huijbregts et al., 2006). Nevertheless, the dominating products are essential to the railway and are basically used similarly in every rail building project. This makes the transition to use the results from the material inventory in the broader system analysis less sensitive to project-specific traits and are important findings for Banverket if they intend to focus their environmental management on their products. However, if the approach is used for specific projects to analyze environmental pressures it is important to point out that if the ballast is not taken from the project site there must be an analysis of the transports to the site since these can have a strong impact on the overall energy use. Furthermore, other studies show that for individual projects the contribution to material-related energy use from tunnels and bridges can be very large (Uppenberg, 2003; Jonsson, 2005).

If we look again at the criteria for evaluating simplified LCA methods in Rebitzer et al. (2004), a conclusion can be drawn that all five criteria are met in this work. The method has a high relevance for Banverket (a) and the results can be used for setting up new environmental strategies. The dependence on only three products makes the results robust and valid and their ranking order would not change (b) if a more detailed approach was used. Since the material use is calculated from the article list which is available for every rail project, the compatibility with Banverket's own systems is good (c). The approach is also very straightforward and involves relatively straightforward and easily gathered data. Thus, it should be fairly easy to reproduce and understand the data and calculations behind the results (d, e).

It is a difficult and demanding task to perform an environmental review or environmental analysis if every single environmental pressure in the studied system is to be included. Thus, sometimes simplification is useful in order to gain usability. The reduction of the complex web of environmental pressures arising from material use to the use of a single material-related energy indicator could make it easier to include an environmental issue, such as upstream environmental pressures, that would potentially be outside the environmental management of an organization. After this initial scoping, further environmental analysis can be carried out, concentrating on the hot spots depicted in this first tentative analysis. Heiskanen (2000) argues that

an important strength of life-cycle assessment tools is that even if they are not used directly in decision-making, they are used to direct attention and inspire new thinking. For an organization that has been focusing most of its efforts on the outflow side of the material use as well as the inflow of toxic substances, it now has a way of gaining more knowledge about the upstream environmental pressures from its inflow of materials. By doing this, it is possible to start to work with the different components of an industrial ecology strategy, as proposed by Ehrenfeld (1994). Furthermore, by introducing a life-cycle perspective to the organization as proposed by the theories behind life-cycle management, it is easier to value trade-offs between the manufacturing-, use- and end-of-life requirements (Hunkeler et al., 2003).

Apart from being used as a basis for introducing life-cycle considerations into Banverket's organization, this approach can be used to investigate new dimensions that are not normally studied within certain tools and processes. For instance, it can be used in EIA or SEA when new transport or building projects are planned. These tools and processes do not usually include upstream environmental pressures from material use (Bruhn-Tysk & Eklund, 2000; Tukker, 2000). Another concept which could use the approach in this thesis is environmental review of organizations similar to Banverket. Since these reviews seldom include upstream environmental pressures, they could make use of a simple and time-efficient tool to at least include them in the reviews (cf. Ammenberg & Sundin, 2005).

5.3 Life-cycle considerations for environmental management in Banverket (Aim III)

The scoping approach proposed in this thesis has been used to find environmental hot spots in Banverket's materials use, which in turn can help to focus and concentrate the environmental management in Banverket. Awareness of what or where these hot spots are can be used in concentrating the efforts in the design of new products. Based on this knowledge, designers can introduce environmental concerns early in the product design process. The technical organization of Banverket, which is responsible for specifications governing product design, is divided into four different railway systems. By showing these divisions what their most important products are, it makes it easier for them to prioritize among different aspects of their environmental management (Figure 11). The track system is the largest contributor for three materials (steel/iron, concrete and crushed rock) as well as overall material use. This can be attributed to the fact that they are

responsible for the use of concrete ties, steel rails and ballast materials. The electrification system uses the bulk of the copper, while in the case of aluminium no individual technical system dominates its use. If environmental concerns were included in the technical specifications for each of the most important products, large environmental benefits could be achieved. However, this would imply large differences from the way the material supply process is structured today since it lacks a life-cycle perspective. Furthermore, the technical departments and the purchasers, who would use the new technical specifications in communication with the suppliers, need and demand a great deal of support and new knowledge through education from other departments in Banverket. This is consistent with other studies which claim that purchasers in other types of organizations feel the same need of support and guidelines from for instance top-level management (cf. Lamming & Hampson, 1996; Heiskanen, 2002). The change from intra-organizational work to expand to inter-organizational work is not an easy task and could involve some radical organizational changes (Sinding, 2000).

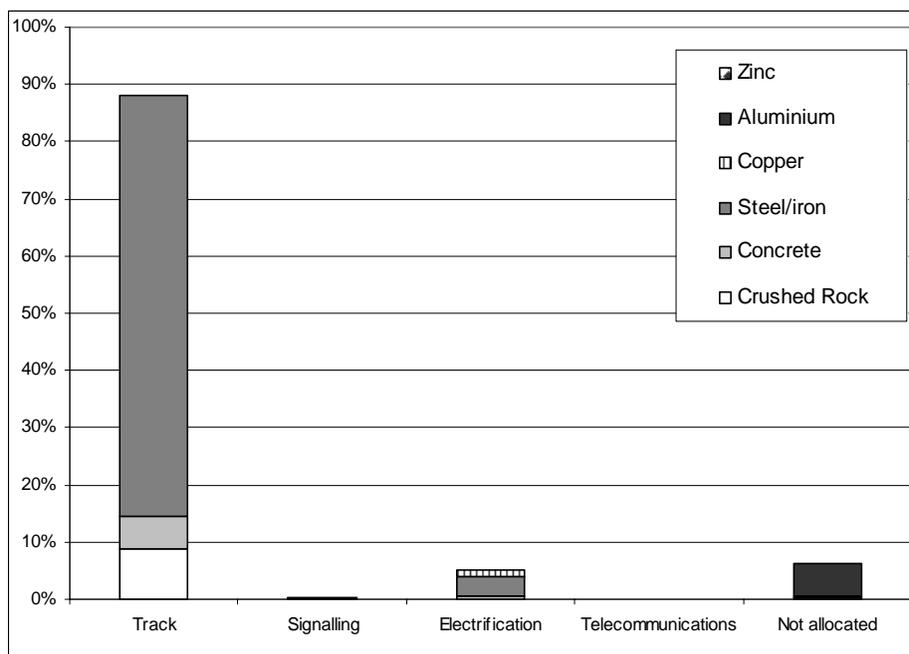


Figure 11: *The contribution to material-related energy use from the four different organizational technical systems in Banverket. Not allocated are a group of articles which cannot be readily attributed to any of the technical systems.*

Environmental requirements in public procurement seem to be rather low in the case of Banverket which is in line with results from other studies (Jonsson, 2004). In the event they are stipulated they are often rather vague or formulated insufficiently (cf. Ibid; Kippo-Edlund et al., 2005; Faith-Ell et al., 2006). Seeing that Banverket in this case is a rather large buyer for some specific products they should be in a good position to extend their environmental requirements. Hall (2000) concludes that environmental supply chain dynamics, i.e. environmental innovations diffused from customer firm to a supplier firm, occur if the customer firm has a certain channel power over their suppliers, has a large technical competence and finally is under specific environmental pressure from other actors. Banverket certainly has channel power over suppliers for some of their products. Furthermore, since the technical department makes the specific technical specifications for each product they clearly possess technical competence. However, there has been low environmental pressure from actors outside the organization concerning these issues which could explain why there has

been rather little activity in setting tougher environmental requirements. It may also be that since the operations phase of the railway is considered to be the largest contributor to environmental pressures, the share from materials use are assumed to be small by the actors in Banverket.

If Banverket were to start to set environmental requirements in purchasing, the results from this thesis could be used to identify which products should be concentrated on in the process. In the case of Banverket, setting tough environmental requirements on its supplier for rails and concrete ties could lead to large environmental benefits in the upstream supply chain. The Best Available Technology (BAT) documents for steel as well as the cement and lime manufacturing industries from the EU shows that there are large differences in energy use between different technologies, indicating that there is great potential for purchasers to set environmental requirements for these materials (cf. European Commission, 2001a; 2001b). A Swedish study indicates that between 35 sites the primary energy use for steel production ranges from about 21 GJ/tonne to about 32 GJ/tonne (Sandberg et al., 2001). If the choice between suppliers to rail would be between these two extremes the material-related energy use would be 35% lower if the best case is chosen over the worst case. Hence, there is a significant improvement potential in setting demands on and making deliberate selection of the rail producers. To bring this even further there is a possibility that in the future Banverket can set demands on a CO₂-neutral rail through the use of CO₂ emission trading on the part of the rail producers. This would obviously mean a tremendous improvement over the fossil-based production currently used. However, these discussions are only hypothetical at this point in time.

The logistics department is also important in the context of this thesis, especially for two particular reasons. First, they are the control station which has easy access to knowledge about the total product use in Banverket. If a similar approach is applied to the total material use in Banverket, they could gain an easily accessible indicator on their total material-related energy use, which in turn could be used in auditing the environmental performance of the railway. Secondly, since the logistics department controls the logistics for the products in different projects, it has an important role in choosing energy-efficient transports for the products. Since many of the products are heavy, transport distances are an important factor in the overall material-related energy use. Similarly, the building contractors are responsible for the product with the largest material use, the ballast materials. Transport distances for the ballast materials can be of utmost importance for the

material-related energy use. Consequently, building contractors should try to use local quarries or use the rock originating from clearing for the track. There is also a possibility to transport the ballast material farther but then it would have to be transported by railway transports.

With the history of Banverket, whose media coverage is dominated by environmental issues related to toxic emissions and hazardous substances, it is possible to partly explain why life-cycle considerations seem to be lacking in the organization. Hill (1997) claims that environmental issues included in decision-making are impacted by the organizational context which he argues includes norms, values and standard operating procedures which are formed by the organization's traditional view of environmental issues. For Banverket it would be close at hand to assume that these views have been greatly influenced by their environmental history. Furthermore, Tyskeng (2006) argues that if the traditional views are formed by early environmental paradigms, the focus would be on local problems from specific sources. The difficulty in translating legislation on global environmental issues such as resource management into easily adapted organizational guidelines can be explained with how this legislation is written. The law regarding resource use is presented generally in the chapter on general rules of considerations and is not specific as the laws governing hazardous substances and toxic emissions which are presented in special ordinances in a special section of the code (cf SFS, 1998). Furthermore, there is a passage which bypasses the general rules of considerations if the cost could be deemed unreasonable for the environmental alternative (cf. *ibid.*). A parallel on the hindrances in translating environmental legislation can be drawn by looking at the difficulty in introducing the resource aspect in development permission processes (cf. Tyskeng, 2006).

6 Conclusions

It is quite a challenge to incorporate life-cycle considerations in an organization whose history is characterized by its work on solving specific local environmental issues. In addition, there seems to be limited pressure from outside and inside the organization to adopt life-cycle environmental management. Furthermore, there is a need for clearer and more specific policy instruments that govern many of the global environmental issues pertaining to material use and its upstream environmental pressures in order to make it easier for organizations to translate them into something useful in their environmental management. The departments with the most capacity to influence the environmental pressures from material use are demanding support and more knowledge about life-cycle considerations in order to set more relevant environmental requirements to their suppliers.

The perceived environmental advantage of the rail transport sector over road transports should not be taken for granted. The importance of the indirect environmental pressures for the rail infrastructure decreases this advantage, since its material-related energy use is almost entirely constituted by non-renewable energy use. If measures are taken by the road transport sector to shift towards vehicles using non-fossil-based energy sources, the advantage could be turned around if the rail transport sector does not act similarly and start decreasing the energy for production of railway infrastructure products or reliance on nonrenewable energy sources for the production.

In order to start working with the environmental management of the railway products there is a need to adopt and introduce new perspectives. The approach developed in this thesis can be used to introduce these perspectives, such as upstream environmental pressures, to the organization's environmental management. It can also be employed to identify hot spots in the organization's material use. Consequently, this new knowledge can be used in the design of new products, to set environmental demands in purchasing and to focus further environmental analyses of the hot spots. The approach can also be used to broaden the perspectives in, for instance, environmental impact assessments, strategic environmental assessments and environmental reviews. The approach uses a single indicator as a proxy for environmental pressures from material use. The relative ease with which this indicator is collected and calculated can make it

possible for the organization to include new environmental dimensions in their environmental management, which could otherwise be outside their expertise, budget or time limit.

The scoping of environmental pressures, by using the approach presented in the thesis, pointed at three important railway infrastructure products. These are the products that Banverket needs to focus on first. One of the most important tasks in incorporating life-cycle considerations on products is to set environmental requirements when introducing new products to the material supply process. The requirements should already be present in the design phase of the products. Thus it is essential that the product developers get the support needed in finding relevant environmental criteria for the new product. One way to accomplish this is to employ an environmental coordinator with sufficient knowledge in the technical departments to work together with the design teams as an integral part of the design process. Setting demands on BAT-technology in producing the rails and ties would lead to significant decrease in environmental pressures from the railway infrastructure.

The overall environmental pressures from the railway transport system depend substantially on the upstream environmental pressures generated by the production of the infrastructure products. These pressures are totally dominated by three products. There is a large improvement potential in focusing the environmental management on these products by posing environmental requirements on their suppliers, in order to decrease the overall environmental pressures generated by the railway transport system.

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8 References

- Alcorn, J. A. & Baird, G. (1996). Use of a hybrid energy analysis method for evaluating the embodied energy of building materials. *Renewable Energy*. 8(1-5):319-322.
- Alcorn, A. (1998). Embodied energy coefficients of building materials. Centre for Building Performance Research, Victoria University of Wellington. CBPR Report Series. 85043.
- Ammenberg, J. (2003). Do Standardised Environmental Management Systems Lead to Reduced Environmental Impacts? Linköping Studies in Science and Technology, Dissertation No. 851, ISBN 91-7373-778-X. Environmental Technology and Management. Linköping University, Sweden.
- Ammenberg J. & Sundin E. (2005). Integrating Design for Environment (DFE) into Environmental Management Systems (EMS) - the role of the auditors. *Journal of Cleaner Production* 13: 417-431
- Ayres RU. (1994) Industrial metabolism: theory and policy. In: Ayres RU, Simonis UE, editors. *Industrial metabolism - restructuring for sustainable development* Tokyo: United Nations University; p. 3-20.
- Banverket. (1996). Kretsloppsanpassning av järnvägens infrastruktur - Handlingsplan 1996. Banverket, planeringsavdelningen. Rapport P 1996:4.
- Bengtsson, M. (2002). Facts and interpretation in environmental assessments of products. Dissertation, ISSN 0345-718X, Chalmers University of Technology, Gothenburg.
- Berkhout F. (1998). Aggregate resource efficiency: are radical improvements impossible?. In: Vellinga P, Berkhout F, Gupta J, editors. *Managing a material world. Perspectives in industrial ecology*: Kluwer Academic Publishers; p. 165-89.
- Boonekamp, P. G. M. (2004). Energy and emission monitoring for policy use Trend analysis with reconstructed energy balances. *Energy Policy*32: 969-988
- Bouwman, M. E. & Moll, H.C. (2002). Environmental analyses of land transportation systems in The Netherlands. *Transportation Research Part D* 7: 331-345
- Bowen FE, Cousins PD, Lamming RC, Faruk AC. (2001). The role of supply management capabilities in green supply. *Production and Operations Management* 10(2): 174-189.
- Boyle, D. K. (1984). Indirect energy considerations in transportation projects. *Transportation Research Record*. 988.

Bruhn-Tysk, S. & Eklund, M. (2000). System boundaries in environmental impact statements for biofuelled energy plants in Sweden. In (ed) Bjarnadottir, H. Environmental Assessment in the Nordic countries- Experience and prospects. Proceedings from the 3rd Nordic EIA/SEA Conference, Karlskrona, Sweden 22nd-23rd November 1999. Nordregio R 2000:3. Stockholm, Nordic Centre for Spatial Development. Pp. 31-38.

Burström, F., 2000. Environment & Municipalities. Towards a Theory on Municipal Environmental Management – With Focus on Capabilities, Roles, Approaches and Tools. Dissertation, TRITA-KET-IM 2000:10. Royal Institute of Technology, Stockholm.

Carpenter, T. G. (1994). The environmental impact of railways. John Wiley, Chichester.

Clift, R. & Wright, L. (2000). Relationships between environmental impacts and added value along the supply chain. *Technological forecasting and social change* 65: 281-295.

Cohen- Rosenthal, E. (2004). Making sense out of industrial ecology: a framework for analysis and action. *Journal of Cleaner Production* 12:1111-1124.

Cole, R. J. & Kernan, P. C. (1996). Life-cycle energy use in office buildings. *Building and Environment* 31(4):307-317.

Connelly, L. & Koshland, C. P. (1997). Two aspects of consumption: using an exergy-based measure of degradation to advance the theory and implementation of industrial ecology. *Resources, Conservation and Recycling* 19:199-217.

Dom, A. (1999). Environmental impact assessment of road and rail infrastructure. In (ed) Petts, J. *Handbook of Environmental Impact Assessment - Volume 2 Environmental Impact Assessment in Practice: Impact and Limitations*. Oxford, Blackwell Science.

Eklund, M. & Svensson, N. (2003). Var i livscykelkedjan sker den största miljöpåverkan för produkter i järnvägens infrastruktur? Report to Banverket (in Swedish).

European Commission. (2001a). Best Available Techniques Reference Document on the Production of Iron and Steel. Integrated Pollution Prevention and Control. December 2001. <http://eippcb.jrc.es/pages/FActivities.html>

European Commission. (2001b). Reference Document on Best Available Techniques in the Cement and Lime Manufacturing Industries. (IPPC) December 2001. <http://eippcb.jrc.es/pages/FActivities.html>

EEA, (1999). Environmental indicators: typology and overview. Technical Report no. 25, 19 p

Ehrenfeld, J. R. (1994). Industrial ecology: a strategic framework for product policy and other sustainable practices, The Second International Conference and Workshop on Product Oriented Policy, Stockholm.

- Faith-Ell, C., Balfors, B. & Folkesson, L. (2006) The application of environmental requirements in Swedish road maintenance contracts. *Journal of Cleaner Production* 14: 163-171
- Fava, H. A. (1997). LCA: concept, methodology, or strategy? *Journal of Industrial Ecology* 1(2): 8–10.
- Fay, R., Treloar, G. & Iyer-Raniga, U. (2000). Life-cycle energy analysis of buildings: a case study. *Building Research & Information* 28(1): 31-41.
- Federici, M., Ulgiati, S., Verdesca, D. & Basosi, R. (2003). Efficiency and sustainability indicators for passenger and commodities transportation systems. The case of Siena, Italy. *Ecological Indicators* 3:155-169.
- Gao, W., Ariyama, T., Ojima, T. & Meier, A. (2001). Energy impacts of recycling disassembly material in residential buildings. *Energy and Buildings* 33:553-562.
- Guggemos, A. A., & Horvath, A. (2005). Comparison of environmental effects of steel- and concrete-framed buildings. *Journal of Infrastructure Systems* 11(2):93-101.
- Guinée, J. B., Ed. (2001). Life cycle assessment: an operational guide to the ISO standards. Part 2A Guide: Ministry of Housing, Spatial Planning and the Environment (VROM) and Centre of Environmental Science - Leiden University (CML).
- Hall, J. (2000). Environmental supply chain dynamics. *Journal of Cleaner Production* 8: 455-471.
- Hill, M. (1997). *The Policy Process in the Modern State*. 3rd ed. Hertfordshire, Prentice Hall/Harvester Wheatsheaf.
- Heiskanen, E. (2000). Managers' interpretations of LCA: enlightenment and responsibility or confusion and denial. *Business Strategy and the Environment* 9:239-254.
- Heiskanen, E. (2002). The institutional logic of life cycle thinking. *Journal of Cleaner Production* 10: 427-437.
- Herendeen, R. A. (2004). Energy and EMERGY analysis - a comparison. *Ecological Modelling* 178: 227-237.
- Hertwich, E. G., Pease W S & Koshland C. (1997). Evaluating the environmental impact of products and production processes: a comparison of six methods. *The Science of the Total Environment* 196:13-29.
- Huijbregts, M. A. J., Rombouts, L. J. A., Hellweg, S., Frischknecht, R., Hendriks, A. J., Van De Meent, D., Ragas, A. M. I., Reijnders, L, Struijs, J. (2006). Is cumulative fossil

energy demand a useful indicator for the environmental performance of products? *Environmental Science and Technology* 40(3):641-648.

Hunkeler, D., Saur, K., Stranddorf, H., Rebitzer, G., Schmidt, W. P., Jensen, A. A. & Christiansen, K. (2003). *Life Cycle Management*. SETAC: Brussels.

ISO (International Organization for Standardization). (1996). *Environmental management systems – specification with guidance for use (ISO 14001:1996)*. Swedish Standards Institution, Stockholm.

ISO (1997) *Environmental management - Life cycle assessment - Principles and framework*. International Standard, ISO 14040:1997.

ISO (1998) *Environmental management - Life cycle assessment - Goal and scope definition and inventory analysis*. International Standard, ISO 14041:1998.

ISO (2000a) *Environmental management - Life cycle assessment - Life cycle impact assessment*. International Standard, ISO 14042:2000.

ISO (2000b) *Environmental management - Life cycle assessment - Life cycle interpretation*. International Standard, ISO 14043:2000.

Johansson, T. B. & Lönnroth, M. (1975). *Energianalys - en introduktion. Framtidsstudien- Energi och Samhälle*. Sekretariatet för framtidsstudier, Stockholm.

Johnston, A., Hutchinson, J. & Smith, A. (2000). *Significant environmental impact evaluation: a proposed methodology*. *Eco-Management and Auditing* 7:186-195.

Johnstone, I. M. (2001). *Energy and mass flows of housing: a model and example*. *Building and Environment*, 36:27-41.

Jones, C. E. (1999). *Screening, scoping and consideration of alternatives*. In (ed) Petts, J. *Handbook of Environmental Impact Assessment- Volume 1 Environmental Impact Assessment: Process, Methods and Potential*. Oxford, Blackwell Science.

Jonsson, A. (2004). *Miljöhänsyn i statliga ramavtal*. Swedish EPA.

Jonsson, D. K. (2005). *Indirekt energi för svenska väg- och järnvägstransporter- Ett nationellt perspektiv samt fallstudier av Botniabanan och Södra länken*. FOI-R—1557—SE (v.2), Swedish Defence Research Agency, Stockholm.

Kahn, A. M. (1980). *Energy efficiency of electrified passenger railway in the Canadian context*. *Journal of Advanced Transportation*, Vol 14, No 13: 237-254.

Kippo-Edlund, P., Hauta-Heikkilä, H., Miettinen, H. & Nissinen, A. (2005). Measuring the environmental soundness of public procurement in Nordic countries. *TemaNord* 2005: 505.

Klinkers L, van der Kooy W, Wijnen H. (1999). Product-oriented environmental management provides new opportunities and directions for speeding up environmental performance. *Greener Manage Int* 1999(Summer):91-108.

Kloft, H. & Wörner, J-D. (1999). Investigations of mass and energy flow in existing buildings. In (eds) Lacasse, M. A., Vanier, D. J. 8th International Conference on Durability of Building Materials and Components (8dbmc). CIB W78 Workshop, IT in Construction. Vancouver, Canada: Institute for Research in Construction, Canada National Research Council Canada, 1999:1426-1435.

Kordi, I., Jonsson, B., Schjelderup, L., Scholander, H., Westerlund, R. (1979), Energieeffektiviteten för person- och godstransporter i Sverige – En jämförande analys, Transportforskningsdelegationen 1979:1.

Korhonen, J. (2002). A material and energy flow model for co-production of heat and power. *Journal of Cleaner Production* 10:537-544.

Lamming, R. & Hampson, J. (1996) The environment as a supply chain management issue. *British Journal of Management* 7(Special Issue):45-62.

Lenner, M. (1999) Energiförbrukning och avgasemission för olika transporttyper, Väg- och transportforskningsinstitutet, *VTI meddelande* 718:1993, 2nd printing 1999. Linköping (in Swedish).

Lenzen, M. (1999). Total requirements of energy and greenhouse gases for Australian Transport. *Transportation Research Part D*, 4: 265-290.

Linnanen L, Boström T, Miettinen P. (1995). Life cycle management: integrated approach towards corporate environmental issues. *Business Strategy and the Environment* 4:117–127.

Maibach, M., Peter, D. & Seiler, B. (1999). *Ökoinventar Transporte- Grundlagen für den ökologischen Vergleich von Transportsystemen und für den Einbezug von Transportsystemen in Ökobilanzen* (2. Korrigierte Auflage). SPP Umwelt, Modul 5, Verlag Infrac. Zürich.

Miser, H. J. and Quade, E. S. (1985). *Handbook of Systems Analysis. Volume one - Overview of Uses, Procedures, Applications and Practice*. Chichester, UK: Wiley.

Moberg, Å. (2006). Environmental systems analysis tools for decision-making - LCA and Swedish waste management as an example. Licentiate thesis, TRITA-SOM 06-002. Royal Institute of Technology, Stockholm.

Nilsson, M., Björklund, A., Finnveden, G. & Johansson, J. (2005). Testing a SEA methodology for the energy sector: a waste incineration tax proposal. *Environmental Impact Assessment Review* 25:1-32.

Odum, H. T. (1971). *Environment, power and society*. Wiley, New York.

Odum H.T. (1994). *Ecological and general systems - an introduction to systems ecology*. Revised ed. of *Systems Ecology*, 1983, University Press of Colorado, Colorado.

Ong, S. K.; Koh, T. H.; Nee, A. Y. C. (1999). Development of a Semiquantitative Pre-LCA Tool. *Journal of Materials Processing Technology* 89/90:572-580.

O'Rourke, D., Connelly, L. & Koshland, C.P. (1996). Industrial ecology: a critical review. *International Journal of Environment and Pollution* 6, Nos. 2/3.

O'Shea, M. A. (2002). Design for Environment in Conceptual Product Design - a Decision Model to Reflect Environmental Issues of All Life-Cycle Phases. *Journal of Sustainable Product Design* 2002(2):11-28.

Quade, E. S. (1995). Predicting the consequences: models and modeling. In (Eds) Miser, H. J. and Quade, E. S. , *Handbook of Systems Analysis - Overview of Uses, Procedures, Application, and Practice*, John Wiley & Sons, Chichester, 1995: 191-218.

Raadschelders, E., Hettelingh, J.-P., van der Voet, E. & Udo de Haes, H. A. (2003). Side effects of categorized environmental measures and their implications for impact analysis. *Environmental Science & Policy* 6: 167-174.

Rebitzer, G., Ekvall, T., Frischknecht, R. Hunkeler, D., Norris, G., Rydberg, T., Schmidt, W.-P., Suh, S., Weidema, B. P. & Pennington, D.W. (2004). Life cycle assessment Part 1: Framework, goal and scope definition, inventory analysis, and applications. *Environment International* 30: 701-720.

Roth, L. & Eklund, M. (2000a). Begrepp och målformuleringar i kretsloppsanpassningen av transportsystemens infrastruktur. KFB- meddelande 2000:17, <http://www.kfb.se/pdf/M-00-17.pdf> (in Swedish).

Roth, L. & Eklund, M. (2000b). Environmental analysis of reuse of cast-in-situ concrete in the building sector. In (eds) Shanableh, A. & Chang, W. P. *Shaping the Sustainable Millennium. Collaborative Approaches*. Brisbane, Australia: Faculty of Built Environment and Engineering, Queensland University of Technology, 2000:234-243.

Sandberg, H., Lagneborg, R., Lindblad, B., Axelsson, H. & Bentell, L. (2001). CO₂ emissions of the Swedish steel industry. *Scandinavian Journal of Metallurgy* 30: 420-425.

Scheuer C., Keoleian G.A. & Reppe P. (2003). Life cycle energy and environmental performance of a new university building: modelling challenges and design implications. *Energy and Buildings* 35:1049-1064.

Seuring, S. (2004). Industrial ecology, life cycles, supply chains: differences and interrelations. *Business Strategy and the Environment* 13: 306-319.

SFS, 1998:808 Environmental Code. Stockholm, Riksdagstryck.

Sinding, K. (2000). Environmental management beyond the boundaries of the firm: definitions and constraints. *Bus Strategy Environ* 2000; 9:79-91.

Smith, R. A. (2003). Railways: how they may contribute to a sustainable future. *Proceedings of the I MECH E Part F Journal of Rail and Rapid Transit* 217: 243-248.

Speier, C. (1998). Using aggregated data under time pressure: a mechanism for coping with information overload. *Proc. 31st Annual Hawaii International Conference on System Sciences*.

Stake, R. E. (1994). Case studies. In: Denzin, N. K. and Lincoln, Y. S. (Eds). *Handbook of Qualitative Research*, Thousand Oaks, Cal. USA, 1994: 86-109.

Stripple, H. (2001). *Life Cycle Assessment of Road - A Pilot Study for Inventory Analysis*, 2nd edition, IVL-rapport, B 1210 E, Gothenburg, Sweden.

Sun, M.; Rydh, C. J.; Kaebnick, H. (2004). Material Grouping for Simplified Product Life cycle Assessment. *Journal of Sustainable Product Design* 2004, 3, 45-58.

Suzuki, M. & Oka, T. (1998). Estimation of life cycle energy consumption and CO₂ emission of office buildings in Japan. *Energy and Buildings* 28:33-41.

Swedish Government. (1998) *Ekologisk hållbarhet*. Government Bill 1997/98:13. Stockholm: Ministry of the Environment.

Thormark, C. (2000). Including recycling potential in energy use into the life-cycle of buildings. *Building Research & Information* 28(3):176-183.

Tukker, A. (2000). Life cycle assessment as a tool in environmental impact assessment. *Environmental Impact Assessment Review* 20: 435-456.

Tyskeng, S. 2006. Environmental assessments of projects and local plans in the energy and waste sectors in Sweden — Practice and potential for improvement. Dissertation No. 1000, Linköping University, Environmental Technology and Management, Linköping.

Udo de Haes, H. A. (2006). Life cycle assessment and the use of broad indicators. *Journal of Industrial Ecology* 10(3): 5-7.

Uppenberg, S., Stripple, H., Ribbenhed, M. (2003). Miljödeklarerad infrastruktur - Metodutveckling för miljöbedömning av infrastrukturssystem. IVL-Rapport, B 1526, Stockholm (in Swedish).

van Berkel R, van Kampen M, Kortman J. (1999). Opportunities and constraints for product-oriented environmental management systems (P-EMS). *Journal of Cleaner Production* 7:447-55.

Vogtländer, J. G., Bijma, A. & Brezet, H. C. (2002). Communicating the eco-efficiency of products and services by means of the eco-costs/value model. *Journal of Cleaner Production* 10:57-67.

Zobel, T. & Burman, J.-O. (2004). Factors of importance in identification and assessment of environmental aspects in an EMS context: experiences in Swedish organizations. *Journal of Cleaner Production* 12: 13-27.