THESIS FOR THE DEGREE OF LICENTIATE OF ENGINEERING

Capturing the life cycle environmental performance of a company's manufacturing system

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This thesis is conducted as part of an industrial PhD project at SKF

Cover illustration:
Development of the life-cycle thinking concept, from no life-cycle thinking, through focusing solely on the manufacturing site, to a general "cradle-to-grave" product focus. Life-cycle thinking is further developed to fit the perspective of a company by relating all life cycle environmental consequences of that industrial actor to its processes. In the last step, this actor's perspective can be narrowed down, considering only the consequences that a particular set of decision makers can influence. The illustration is found at page 6 in this thesis.

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ABSTRACT

This research has developed methods for manufacturing decision makers to measure manufacturing environmental performance and to predict the environmental consequences of alternative manufacturing system configurations. The ideas behind the methods are based on life-cycle thinking from the perspective of an industrial actor, and its decision makers, in the value chain of a product. The ideas are to (1) focus on the parts of the product life cycle that manufacturing decision makers can influence, (2) relate environmental consequences to changes in a manufacturing system, and (3) use a model in which discrete-event simulation (DES) is used to capture the dynamic features of a manufacturing system and life-cycle assessment (LCA) is used to quantify the life cycle environmental consequences.

The aim has been to enable manufacturing decision makers to understand the environmental consequences of their actions. To do this, the ideas were further developed using a case study of a bearing unit production line. From the experience gained in that case study and from the knowledge foundation in previous published work we have developed three main methods.

The first is a method to relate environmental consequences to a manufacturing actor when performing a life-cycle assessment (LCA), this to increase the relevance of results and the probability to find ways to improve the system. The second method suggests how system boundaries in an LCA can be drawn to specifically measure the environmental performance of an industrial actor's manufacturing system. This is done by only considering this manufacturing system's *material losses* and *energy use* when calculating its environmental impact. Finally, to capture the dynamic characteristics of a manufacturing system and enable what-if scenarios for changed production configuration, four methodological sub-proposals are suggested to create a DES-LCA model.

Keywords: Manufacturing decision making, LCA, DES, actor

LIST OF PUBLICATIONS

PAPERS INCLUDED IN THE THESIS

Paper I

Löfgren, Birger, Anne-Marie Tillman and Björn Rinde. ”Measuring life-cycle environmental performance of manufacturing from an industrial actor’s perspective."

Submitted in December 2009 to *Journal of Cleaner Production*.

Paper II

Löfgren, Birger and Anne-Marie Tillman. ”Relating manufacturing system configuration to life-cycle environmental performance: discrete-event simulation supplemented with LCA."

Submitted in December 2009 to *Journal of Cleaner Production*.

OTHER PUBLICATIONS BY THE AUTHOR

Löfgren, Birger (2007). Added value of following ISO14044 allocation rules for electricity use in manufacturing industry. SETAC Europe 14th LCA Case Studies Symposium, Göteborg, Sweden, 3-4 December, 2007.

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This research has been carried out as part of an industrial PhD project at SKF Group Manufacturing Development Centre (MDC). I want to thank the manager of MDC for his firm support and for providing me the opportunity for scientific work in close collaboration with university. My industrial supervisor at Group Sustainability has been a mentor and great source of inspiration, already before I started the PhD project at SKF. I also want to thank my immediate manager for his deep engagement in my work, his enthusiasm and inspiring discussions.

This PhD project is part of a larger project at SKF developing methods and tools for environmental decision making throughout the organisation. I want to thank everyone involved in that project, but especially Björn Rinde for his important feedback on the ideas and methods that are presented in this work.

My background in physics and industrial ecology have been complemented with essential knowledge in production engineering thanks to the research program at Centre for Advanced Production Engineering, that also partially funded the research. I want to thank my academic co-advisor Johan Stahre and his associates for giving me specific knowledge in production simulation.

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1. INTRODUCTION

At this writing moment governmental officials and their negotiators are struggling to agree on what can be settled at the UN Copenhagen Climate Change Conference in December 2009. NGOs, such as the WWF [1], are hoping for an aggressive international cap-and-trade deal replacing the Kyoto protocol in 2012, when the first global treaty with binding targets for emitting greenhouse gas emissions is expiring. Global warming is, however, only one example of global environmental challenges that we are currently facing. A recent article, published in the journal Nature, defines nine planetary boundaries “that must not be transgressed” in order for humanity not to provoke irreversible environmental change [2]. The analysis shows that we have passed the “safe operating space” for global warming, but at the same time this boundary has not yet been overstepped as far as the boundaries for biodiversity loss and for polluting freshwater assets with nitrogen emissions.

To address these challenges all actors, small or large, need to contribute; policy makers, the society and consumers, and industry. Like many other companies around the world, SKF therefore shares the challenge of reducing increasing human pressure on the global, regional, and local environments. The research initiative is part of SKF’s response to that challenge, and intends to develop methods for continuously improving the environmental performance of its operations and products via practical life-cycle thinking. This initiative is based on a belief that it is equally important to involve all decision makers on the corporate micro-scale as it is to include all actors on a societal macro-scale. Or expressed differently, from the perspective of a specific decision maker, how can he/she contribute?

1.1 THE RESEARCH IDEA AND AIM

This research further develops an idea that could allow manufacturing decision makers to understand the environmental consequences of their actions. The idea is to

- focus on the parts of the product life cycle that manufacturing decision makers can influence,
- relate environmental consequences to changes in a manufacturing system, and
- use a model in which discrete-event simulation (DES) is used to capture the dynamic features of a manufacturing system and life-cycle assessment (LCA) is used to quantify the life cycle environmental consequences.

1.2 RESEARCH METHOD

A practical case study was used to explore how the idea could be transformed into an applied method. During the process of developing a DES-LCA model of an SKF production line, data collection, conceptual model construction, and computer implementation were carried out simultaneously. The literature was reviewed throughout the process, from project start-up to writing the thesis. It must be emphasized that the results of the case study, described in the appended papers, are not the main results of the research; rather, they were used in the process of refining the initial concept into a method. Fig. 1 depicts the research method, from need and problem formulation, through idea and case study, to case results and methods.

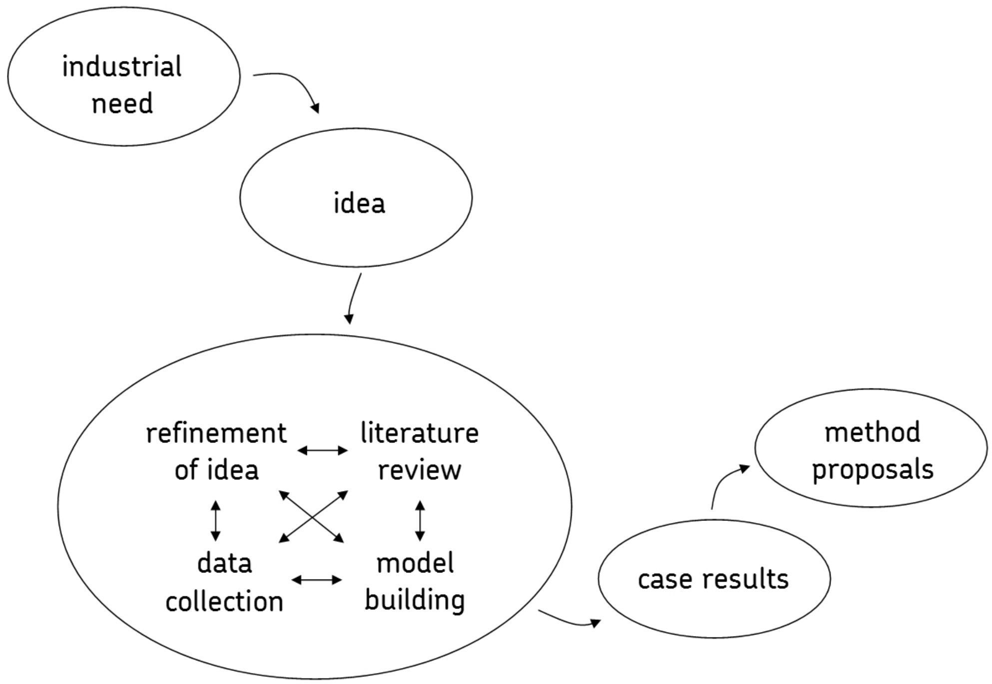

Fig. 1. *Research method: a problem was formulated, generating an idea that was refined in a case study.*

2. BACKGROUND

This background section starts by outlining the international activities that define the political movement for sustainable consumption and production and how this movement can be seen as both a challenge and an opportunity for the manufacturing sector. The section continues by describing the industrial development of environmental management, using parallels to how quality management has been adopted by industry. The concepts of life-cycle management (LCM) and life-cycle thinking are defined, followed by identifying a few prerequisites for effectively adapting manufacturing environmental management to this new perspective. Based on the specific attributes of a manufacturing system, two methods are selected that, together, could capture the desired features needed to support manufacturing decision making by offering a life-cycle perspective of the manufacturing processes.

2.1 SUSTAINABLE CONSUMPTION AND PRODUCTION IN THE INTERNATIONAL COMMUNITY

The first major conference on international environmental issues, the United Nations Conference on the Human Environment, was held in Stockholm in 1972. Fifteen years later, in 1987, *Our Common Future* was published by the World Commission on Environment and Development, also known as the "Brundtland Commission". The report contains a standard definition of sustainable development, namely, "development that meets the needs of the present without compromising the ability of future generations to meet their own needs" [3]. The work set a foundation for the UN Earth Summit held in Rio de Janeiro in 1992. The outcomes of that conference were the Rio Declaration containing 27 principles for sustainable development, the Agenda 21 programme for sustainable development, forest principles, and two legally binding conventions: the Convention on Biological Diversity and the Framework Convention on Climate Change, which adopted the Kyoto protocol in 1997.

At the follow-up meeting in 2002, the World Summit on Sustainable Development, the Johannesburg Declaration on Sustainable Development was formulated. This document further committed the world's nations to sustainable development. It also gave authority to the Marrakech Process, a 10-year framework to promote and accelerate the shift towards sustainable consumption and production. One of three goals of the Process is to help corporations develop greener business models. The first expert meeting was held in Marrakech in 2003 and the latest took place in Stockholm in summer 2007. Parallel to the Marrakech Process, several initiatives were taken to facilitate the integration of environmental considerations into corporate affairs. Among these are the business-driven World Business Council for Sustainable Development (WBCSD), the Society of Environmental Toxicology and Chemistry (SETAC), and the United Nations Environmental Programme (UNEP) partnership, the Life Cycle Initiative.

2.2 THE INDUSTRIAL CHALLENGE: POLICY ACTION PLAN AND BUSINESS ARGUMENTS

On 16 July 2008, the European Commission presented the Sustainable Consumption and Production and Sustainable Industrial Policy (SCP/SIP) Action Plan, which charts the direction of future European policy measures. The Action Plan explicitly considers the life-cycle perspective, for example, via the Integrated Product Policy, as well as, via promotion of leaner and cleaner production through "resource efficient and eco-innovative production processes" [4, p.8]. This implies that more stringent policy measures are around the corner, putting more pressure on the manufacturing industry, among other actors, to develop its business along the sustainable development path. The driving force of this industrial challenge, however, is not only the challenge of new, stricter environmental regulation. Several studies have identified the business rationales for considering the environmental performance of products and production processes [5-15]. Perhaps the most famous such studies are those of Porter and Van der Linde [16-17], who argue for the link between environmental performance and competitiveness.

2.3 THE SHIFT FROM END-OF-PIPE TO "CREATIVE RESPONSES": THE QUALITY ANALOGY

The way industry has worked with the environmental aspects of their products and processes has many parallels to how quality management has developed.

For many years, manufacturing environmental management was focused on taking care of emissions and waste *after* they had been produced. Starting in the 1970s, it was suggested that such "end-of-pipe" solutions should be replaced by (1) considering the value of the waste and (2) changing the production process to prevent the emissions and waste from being produced [18-21]. In the early 1990s, multinational companies based in countries with more intense environmental regulations had started to develop environmental strategies [22]. Environmental management systems started to appear, intended to control and structure efforts related to the company's environmental influence, including the introduction of the ISO 14000 management standards in 1996 [23] and the EMAS management standards in 1995 [24]. These standards were built on the same framework as the ISO 9000 quality management system, that is, fostering continuous improvement by following the plan–do–check–act cycle [25]. Parallel to this management standard for structuring and following up on quality control measures, industry developed the concept of total quality management (TQM) for effectively improving quality performance.

TQM was an industrial response to the superior performance of Japanese manufacturers [26]. Florida [27] identifies the method as an example of how industry can be creative in responding to new needs by completely changing how business is carried out. He refers to Schumpeter's work describing an economy's ability for such a "creative response" to changed conditions versus simply increasing business-as-usual efforts, referred to as "adaptive response" [28]. In the mid 1990s, Florida also saw the "emergence of creative responses" where companies developed innovative manufacturing systems to increase both conventional industrial and environmental performance [27].

Similar to how the shift from end-of-pipe solutions changed environmental management, TQM changed the perspective of quality work from being something that was implemented by checks just before the product was packed and distributed to the customer to being implemented by measures to prevent errors before they occurred. However, since this quality concept is a "comprehensive and integrated way of managing any organization in order to meet the needs of the customers consistently and achieve continuous improvement in every aspect of the organization's activities" [29, p.2], it is more ambitious than the environmental work started in the 1970s and identified by Florida in the 1990s, when process innovations was applied instead of end-of-pipe solutions to prevent environmental problems.

A framework for sustainability management was formulated by the Organisation for Economic Co-operation and Development (OECD) in 1992, as part of developing a sustainable product policy [30]. The concept, life-cycle management (LCM) relates to previous environmental management standards as TQM relates to the IS0 9000 system, by focusing more on how a company can improve the environmental performance than how to control and structure the work.

LCM was further developed for three years by SETAC Europe, which published the results as a book to "introduce and encourage better if not best practices in LCM" [31]. In 2002, SETAC and UNEP launched LCM as one of the three programmes in the Life Cycle Initiative. Although many companies have been involved in developing methods supporting LCM (e.g., eco-efficiency by BASF [32], the LCM matrix at 3M [33], and information modules at ALCAN [34]), it is far from being adopted by industry to the same extent as TQM[1].

Even though the name LCM was coined by the OECD, the emergent industrial interest in developing and applying LCM can be seen as a creative response to a changing business environment where sustainability aspects are increasingly becoming an integral part of business strategies for competitiveness.

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[1] During the 1990s, several authors [35-39] suggested that TQM be extended to include environmental quality factors, under the name total quality environmental management (TQEM) to clearly state its relationship to TQM. TQEM inherited the tools and methods used in TQM, adapting them to consider the environmental needs of the customer. TQEM has many similarities to LCM. Two differences are that LCM includes social aspects in addition to environment, and that LCM has a clear life-cycle perspective. Even though the TQEM literature includes references to LCA, the life-cycle perspective is not particularly evident in the TQEM process. As with LCM, TQEM is not adopted by industry to the same extent as the original concept TQM.

2.4 DEFINITION OF LIFE-CYCLE MANAGEMENT AND LIFE-CYCLE THINKING

LCM has recently been defined by the Life Cycle Initiative as aiming to “minimize the environmental and socio–economic burdens associated with [a] product or product portfolio throughout its entire life cycle and value chain. LCM makes life-cycle thinking and product sustainability operational for businesses through continuous improvements” [40, p.5]. However, not everyone defines the environmental aspects of product performance as part of LCM. A less normative formulation, not explicitly claiming that LCM leads to better environmental performance, can be found in Baumann and Tillman [41], who define LCM as “managerial practices and organizational arrangements in a company or product chain that are expressions of life cycle thinking”.

Life-cycle thinking, which is the foundation of both definitions, can be defined as “a way of thinking that considers cradle-to-grave implications of different applications and products without going into the details of an LCA study” [41, p. 532]. The concept of life-cycle thinking used in the present work is, however, more normative. The method proposed in this thesis assumes life-cycle thinking from the perspective of a specific actor in the product life cycle (see Fig. 1), meaning that this industrial actor acknowledges and actively responds to the life-cycle environmental consequences of his/her products or processes. Fig. 2 illustrates how this perspective can be linked to a more conventional definition of life-cycle thinking, focusing on the product. The figure also shows how life-cycle thinking can be further developed to refer to a corporate decision maker considering the environmental consequences *that he/she can influence*.

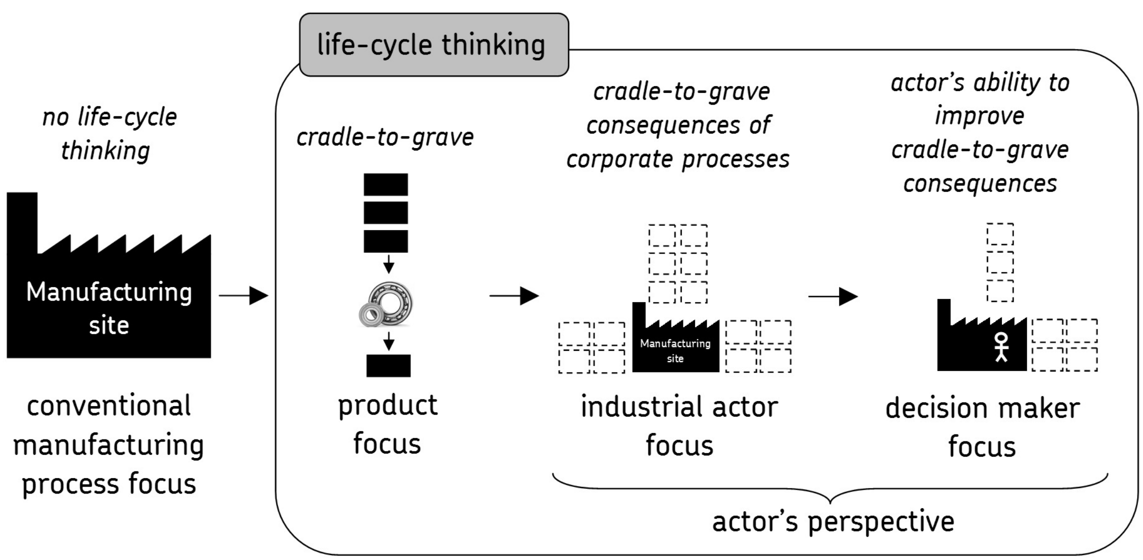

Fig. 2. *Development of the life-cycle thinking concept, from no life-cycle thinking, through focusing solely on the manufacturing site, to a general “cradle-to-grave” product focus. Life-cycle thinking is further developed to fit the perspective of a company by relating all life cycle environmental consequences of that industrial actor to its processes. In the last step, this actor’s perspective can be narrowed down, considering only the consequences that a particular set of decision makers can influence.*

The point of defining life-cycle thinking this way is to highlight the environmental consequences that a specific actor (i.e., a company in the value chain or a decision maker in a company) has the power to influence. This focus highlights an important feature of successful LCM implementation, namely that of including all decision makers on the process.

2.5 INCLUDE ENVIRONMENTAL CONSIDERATIONS IN CURRENT TOOLS

Conventionally, corporate environmental management has been the task of the environmental health and safety personnel and environmental department of a company. It has been emphasized [42] that this responsibility structure is not suited for supporting effective environmental strategies in a manufacturing company. Returning to the quality analogy, the success of TQM lies in the fundamentals of the concept, which is empowerment by making everyone responsible for quality. In fact, the "T" for *total* in TQM specifically refers to the involvement of *everyone* in the quality management process [26]. It is therefore likely that LCM can be as successful as TQM, if tools and methods developed to support LCM target *all* decision makers in a company, enabling them to investigate how they can influence the company's environmental performance. Furthermore, to simplify the learning process, which is generally seen as a critical parameter for successful implementation and organizational change [43], it is probable that it is more efficient to adapt current systems and tools to support life-cycle thinking, instead of inventing entirely new methods or using existing methods that are new to the organization.

A fundamental method for applying life-cycle thinking is LCA. The method may not be suited to support decision making in daily work. However, an important role of LCA in industry has been to help companies gain a general understanding of the environmental consequences of their products from a life-cycle perspective [44].

2.6 LCA AND ITS LIMITATIONS IN SUPPORTING MANUFACTURING LCM

LCA is as an ISO standard method for quantifying the environmental consequences related to a product throughout its life cycle, which normally means that everything from raw material extraction to product manufacturing, use, and disposal is considered. It can be used for decision making (e.g., product design and development), learning and exploration (e.g., environmental characterization of a production system), or communication (e.g., asserting environmental product claims). LCA, however, is a scientific methodology not developed to suit all industrial procedures and processes. Other methods have been developed that can more efficiently be applied in specific business processes. The most common such method is design for the environment (DfE), which supports product design by e.g. applying simplified LCA methods.

In LCA procedure, a life-cycle model of the product is constructed, and inputs and outputs for each process in the model are quantified and calculated as either resource use or emissions in the product life cycle. Those inputs and outputs that represent emissions or natural resource use are interpreted as potential impacts on the environment.

Fig. 3 depicts the value chain of a product life cycle. When assessing the environmental consequences of manufactured products, often only part of the life cycle is considered. One type of such a partial assessment is the "cradle-to-gate" study, which considers all processes from raw material extraction to the "gate" of the production facility distributing the finished product.

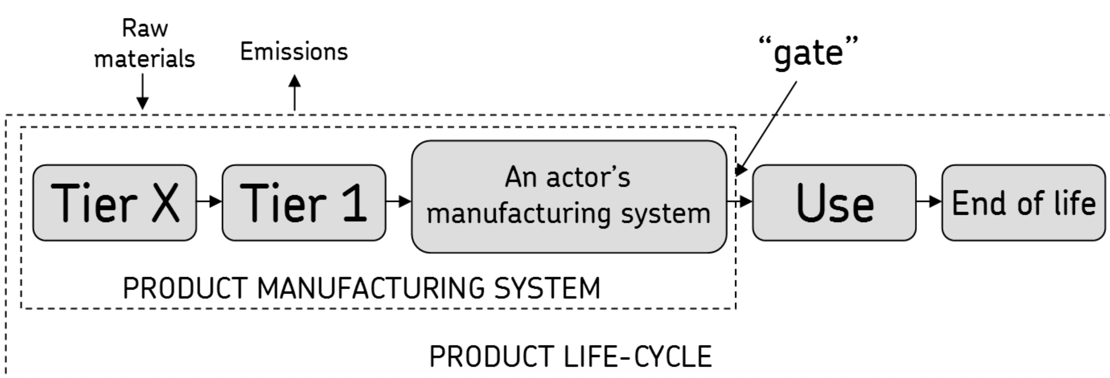

Fig. 3. The complete product life cycle extending from "cradle to grave". The product manufacturing system includes the actor's manufacturing system and its suppliers delivering directly to the actor (i.e. tier 1) all the way up to the very beginning of the value chain (i.e. tier 2,…,x).

A common interpretation method in LCA is to compare the relative contributions of different parts of the life cycle in what is called contribution analysis [45]. Paper I points out that this method fails to support manufacturing LCM, since it disregards the decision domain of the corporate decision maker and does not relate particular environmental consequences to their root causes. Consequently, this might lead to the disregarding of improvement potentials and discourage decision makers from taking action in cases where much or most of the environmental impact seems to lies outside their scope of influence. Furthermore, in assessing scenarios of changing production system configuration, LCA methodology falls short by being unable to mimic a system possessing the characteristics of a manufacturing system, see paper II. To assess the environmental consequences of changing the manufacturing configuration, the static LCA methodology needs to be complemented by another modelling approach that captures the dynamic interrelationships between manufacturing processes. A simulation method that has been developed for this purpose is discrete-event simulation (DES).

2.7 DES IN BRIEF

DES is one of several methods in the operations research area that mixes mathematical modelling and statistics to arrive at near-optimal solutions to the problems of complex systems, such as manufacturing systems. Operations research seeks to supply quantitative information to serve as a basis for decision making. Alternative methods applied in operations research include game theory, queuing theory, and decision analysis. These methods are based on either analytical modelling or simulation; in the latter, the real dynamic process is imitated through its temporal progress, as in the case of DES.

DES is commonly used in industry to improve the performance of production systems, especially in manufacturing, and normally focuses on improving production line throughput by e.g. bottleneck identification and investigating resetting procedures. It is an event-driven simulation, which means that events are executed in accordance with a list of events. These events in turn trigger new events that are continuously added to the event list. This event list drives the simulation progress in time. In the practical application of DES, the manufacturing process is mapped as the parameters that have a probable influence on the objective function (response) of the study. Such parameters can be labour requirements, cycle times, resetting times, and production hours. Together with statistical data on interventions (e.g., in response to machine breakdowns) that may influence the response and the relationships between all these parameters, the model can be implemented as a computer model.

Unlike most LCA models, DES simulations should, due to their stochastic behaviour, be set up and interpreted with a view to statistical validity. This means that the statistical distributions of input data, simulation length, number of replications, and confidence intervals for results should be considered carefully.

3. LITERATURE REVIEW

This review summarizes the literature that has been presented in the appended papers. The review is discussing (1) actor's perspective in LCA, (2) advanced analytical LCA models, and (3) the use of DES for environmental assessment.

3.1 ACTOR'S PERSPECTIVE IN LCA

Commenting on studies exploring LCA's popularity among market actors, Heiskanen [46] concludes that conventional LCA results can be disempowering when presented to decision makers or customers; she therefore suggests that it would be better to present results in a form that indicates *how* these actors can improve the environmental performance of the product or service. A step in this direction is taken by Baumann and Tillman [41], who propose a method to indicate the actual influence a decision maker has on the processes in a life cycle. Presenting LCA results in this way, with the actor's perspective in mind, has been further discussed and developed [47-48].

3.2 ADVANCED ANALYTICAL LCA MODELS

When considering LCA tailored to the needs of a specific actor in the value chain, it is usually possible to increase the model detail of the parts of the chain that this actor can influence. Berlin et al. [49] developed a model for minimizing waste in dairy production. Finnveden et al. [50] give several additional examples in which analytical methods applicable to parts of a life cycle are developed. The cited examples pertaining to waste and water management, agricultural pesticide emissions, chemical and cement production, however, include models developed both to support specific actors and to reduce the amount of input data that needs to be collected in an LCA. The use of advanced simulation models incorporating LCA to support process engineers was introduced by Azapagic et al. [51-52]. After that, methods supporting environmental management in process industries, such as chemical production and oil refining, were addressed by several authors [48, 53-58]. A principle common to many of these methods is to use a more advanced model to calculate material and energy use of the processes in focus, and multiply the output of this model by factors representing upstream and downstream environmental consequences. These factors are either modelled specifically for the study using LCA or acquired from an LCA database. The same principle is also found in advanced simulation models for the environmental assessment of manufacturing systems using DES.

3.3. DES FOR ENVIRONMENTAL ASSESSMENT

In identifying the requirements for modelling manufacturing processes, Wohlgemuth et al. [59] were the first to perform environmental assessment using DES. Their method linked material flow analysis software, used for static calculations similar to LCA, with a dynamic DES modelling tool; a similar approach was also used by Reinhard and Motsch [60]. Heilala et al. [61] presented an integrated DES method including automation level, ergonomics, and environmental assessment. The method they used to include environmental aspects in DES was developed in three separate case studies of the food industry [62-64]. DES has also been used to perform energy calculations in the foundry industry [65-66]. A more detailed approach, using DES, to analysing energy use in a manufacturing process was suggested by Dietmair and Verl [67].

Furthermore, the use of DES methodology has been proposed for assessing the long-term consequences of different urban water strategies [68] and for investigating recycling strategies [69]; it has also been explored as an alternative approach, to that applied in current LCA software, for modelling the whole product life cycle [70].

The research presented here follows up Heiskanen's ideas by further developing the actor's perspective to address the specific needs of manufacturing actors. The ideas are taken further, and the approach is used for more than simply measuring a manufacturing system and presenting the results in a way relevant to the actor. A methodology for using DES to simulate the actor's manufacturing system is developed, based on the principles of earlier environmental simulation methods used in both the process and manufacturing industries.

4. PROPOSALS FOR MANUFACTURING LCM

Three main methods have been developed in this work, of which the first two are presented in paper I and the third in paper II. These are: (1) a way to present LCA results that relates environmental consequences to a particular industrial actor, (2) a way to measure the environmental performance of this actor's manufacturing system, and (3) modelling choices for using DES, in combination with LCA, to investigate the influence manufacturing decision makers have on the environmental performance of an actor's manufacturing system. The description below outlines the features of these methods that differ from previously published methods.

4.1 RELATING RESULTS TO A MANUFACTURING INDUSTRY ACTOR

In conventional LCA, contribution analysis results are presented broken into the different parts of the life cycle. Fig. 4 illustrates this by showing the relative global warming emissions of a cradle-to-gate system consisting of SKF in-house manufacturing processes, tier-1 suppliers' processes, steel production, and other suppliers' processes. From this diagram it may seem as though SKF manufacturing processes account for only approximately one fourth of total emissions. However, applying life-cycle thinking, in which all actors in the value chain acknowledge and actively responds to the life-cycle environmental consequences of their products or processes (with reference to *Fig. 2*), the same results can be presented as in Fig. 5. Here, *all* emissions are related to SKF processes, together with their relative contributions (in descending order): production of material in the finished product, production of material machined away in SKF processes, production of electricity used in SKF processes, and production of components scrapped in SKF processes.

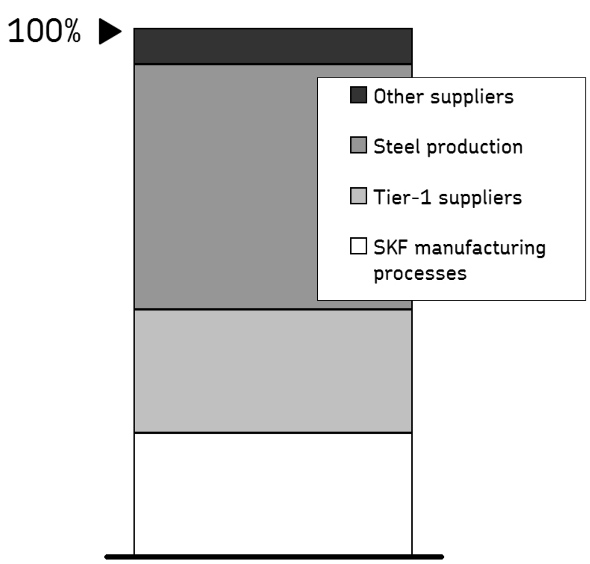

Fig. 4. *Contributions to global warming from manufacturing a bearing unit (cradle-to-gate).*

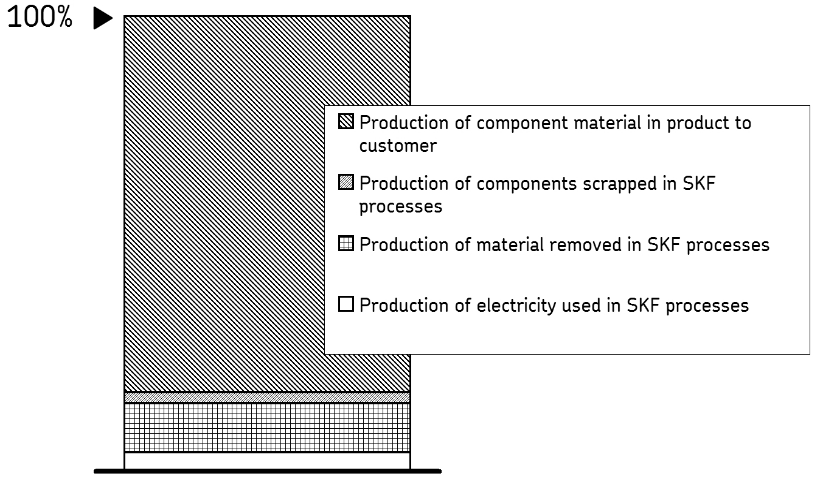

Fig. 5. *Contributions to global warming from manufacturing a bearing unit, presented relating cradle-to-grave environmental consequences to SKF processes. The same data and system boundaries are used here as in Fig. 4.*

A similar analysis may be done for any actor in the value chain, such as from the perspective of SKF tier-1 suppliers. In such as case the results would be different compared to Fig. 5, since environmental consequences would be related to that actor instead of to SKF. This means that results presented this way is not additive, namely that adding e.g. tier-1 results to SKF results would be double-counting environmental consequences.

4.2 SYSTEM BOUNDARIES FOR MANUFACTURING ENVIRONMENTAL PERFORMANCE

Fig. *6* depicts the processes included in a cradle-to-gate LCA model of a manufacturing system. When assessing the environmental consequences related to manufacturing the product of a specific industrial actor, all the processes located upstream of the factory gate are normally included. These include the actor's in-house manufacturing processes and the production of energy carriers used in them, production of direct material (i.e., product components), production of indirect material (i.e., material used in the actor's process but not as part of the product), production of capital goods (e.g., the actor's machinery and buildings), and the processes required to treat and/or handle manufacturing residues. The material losses in the actor's manufacturing system can be defined as all the material not ending up in the product at the factory gate. Consequently, material losses include everything from metal chips machined away from workpieces and scrapped parts to tooling and worn-out machines.

In focusing on the factors that decision makers controlling the manufacturing processes can influence, it is useful to define the environmental performance of the manufacturing system. Even if energy use and material losses in the manufacturing systems could be completely eliminated, the environmental impact of manufacturing, defined as including all the cradle-to-gate processes, would not be zero. The direct material in the product would still need to be produced, leading to environmental consequences. To single out the environmental consequences related to a specific manufacturing system in the value chain, the production of this material – shaded in grey in Fig. 6 – could be omitted from the analysis. This puts the focus clearly on reducing waste, defined as energy use and material losses, in the part of the system that manufacturing decision makers can influence directly.

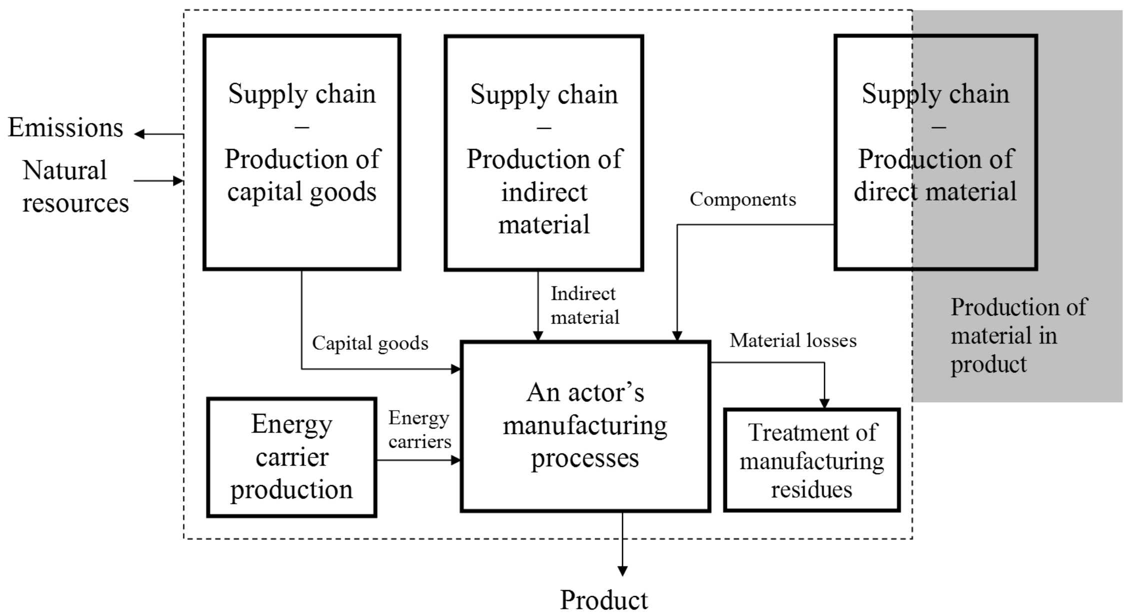

Fig. 6. *System boundaries, represented by dotted lines, when relating environmental consequences to an actor's manufacturing processes. The supply chain production of capital goods, direct and indirect material, and energy carriers includes all upstream processes required for production. The part corresponding to the material in the product is partitioned away from the processes for producing direct material.*

Fig. 7 shows the greenhouse gas emissions related to SKF manufacturing processes, with system boundaries as in Fig. 6. Data is taken from the same study used to produce Fig. 4 and Fig. 5. Presented in this way, the material that is machined away from workpieces in SKF processes contributes most to greenhouse gas emissions.

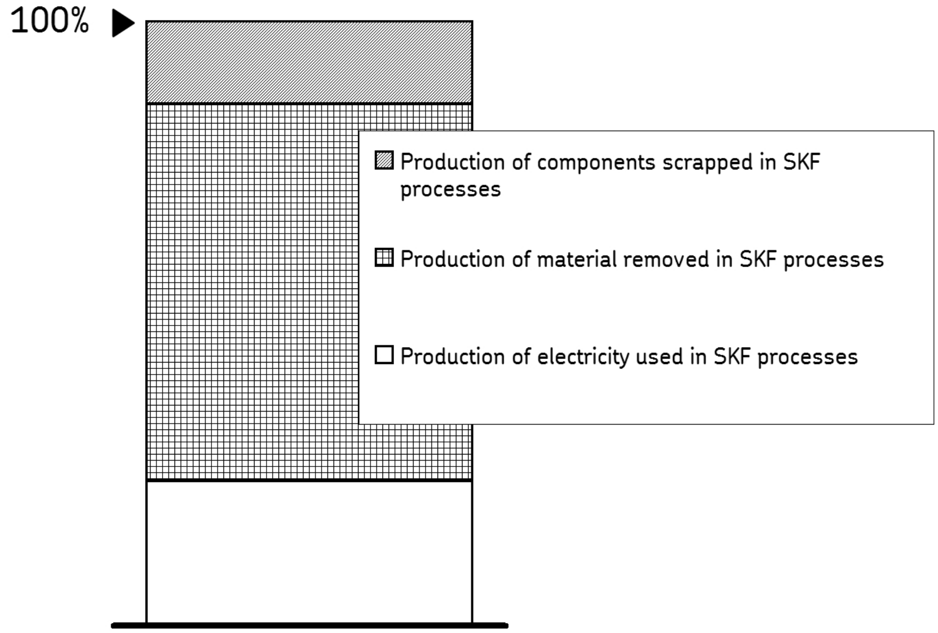

Fig. 7. *Contributions to global warming from SKF manufacturing processes, with system boundaries according to Fig. 6.*

4.3 USING DES TO CAPTURE THE DYNAMICS OF THE MANUFACTURING SYSTEM

Including environmental aspects in a DES model is not a new idea, and the method presented here represents a refinement of previous ideas on how to do this. The method aims to help manufacturing decision makers find ways to improve the environmental performance of processes for which they are responsible. To do this, the proposed method includes four methodological sub-proposals: (1) using DES to calculate manufacturing processes' energy use and material losses in the system, (2) developing "LCA factors" to represent the environmental consequences of this energy use and material loss outside the actor's manufacturing system, (3) a method for machine energy use, and (4) a proposed method for showing decision makers the environmental consequences of a particular decision.

4.3.1 Calculating environmental performance per manufacturing process

We have found two ways to calculate the environmental performance of the manufacturing system using simulation; either allocated to the products being produced or to production processes. Using a product perspective, it may be reasonable to relate the environmental impact to the material streams in the system. In this case, each product will accumulate environmental impact as it progresses through the production system. The total environmental impact of the system is then the sum of the environmental impact of all produced products. This approach is common in process industry simulation (see, e.g., Bauer and Maciel Filho [54]). To shift focus from the product to manufacturing processes, the present work proposes instead to calculate the energy use and material losses of each process. The total environmental impact of the system is then the sum of the environmental impact of all processes. This is the method we propose for assessing the environmental performance of the manufacturing system, since it is better aligned with how environmental performance is defined, see section 4.2.

4.3.2 LCA factors

Given the stated definition of the environmental performance of a manufacturing system, the environmental consequences of the system can be expressed as the sum of the environmental consequences of the system's various constituent energy uses and material losses, as follows:

$$Env.\ conseq. = \left[from\ material\ loss + from\ energy\ use\right] = \sum_m \left(pm_m + t_m\right) M_m + \sum_e pe_e E_e \ ,$$

where

pm = LCA factor for upstream material production, such as components, indirect material, or capital equipment,
pe = LCA factor for upstream energy production,
t = LCA factor for treating manufacturing residues (material losses),
M = material loss,
E = energy use,
m = index for each type of material, and
e = index for each type of energy carrier.

The overall LCA factors are obtained by using LCA to model the individual systems that produce the components, indirect material, capital goods, and energy carriers, and the processes to treat manufacturing residues. In Fig. 8, the grey areas represent such LCA models, in the case of manufacturing a bearing unit at SKF. LCA factors can be expressed as individual emissions or resource uses included in a life-cycle inventory (LCI) or as a further assessed category indicator (e.g., carbon dioxide equivalents, CO_2-eq.) in a life-cycle impact assessment (LCIA).

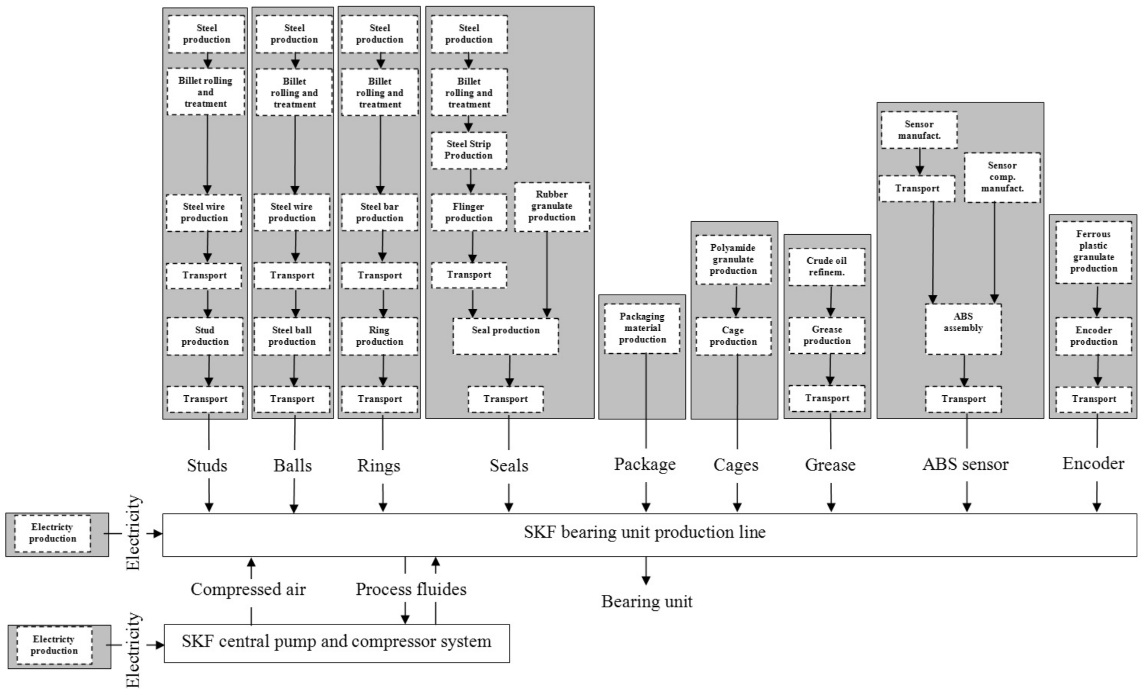

Fig. 8. *LCA modelling used in Rinde [71] to calculate the LCA factors of components and electricity supplied to the SKF production line. Each grey box represents a system modelled using LCA to calculate the environmental consequences of a component or electricity input to the SKF production line.*

4.3.3 Machine energy use

The energy used by a production machine can be modelled in great detail, using the physical relationships of the process itself, such as material removal in machining and heating and cooling in heat treatment. For the purpose of production line simulation, a simpler model is suggested and used in the case study in paper II: energy use is divided into three typical operation modes, i.e., running, waiting, and unmanned hours.

Running mode is how a machine operates during normal, undisturbed production, when a machine is continuously fed workpieces at the pace of the machine’s current cycle time. *Waiting mode* – when a machine waits for new workpieces to arrive – can occur for several reasons, including unbalanced production, machine breakdowns, and resetting. *Unmanned hours mode* is representing machine status when production is closed, such as during weekends and holidays.

Production line machines commonly use electricity directly (e.g., in electric motors) and indirectly via other energy carriers (e.g., compressed air, hydraulic oil, and process media for cleaning, cooling, and/or lubricating the process). It is suggested that, when these energy carriers are produced by a central pump and compressor system, the electricity used for that process be assigned to the production line machines *using* the energy carriers, instead of to the central pumps and compressors *producing* it. This is done by calculating the central system's electricity use per volume of energy carrier, using a flow-to-power conversion factor, system-specific power (SSP), as follows:

$$SSP_i = \frac{E_i}{V_i} \ ,$$

where E_i is the electricity use and V_i is the annual throughput for energy carrier i. The machine energy carrier flow, Q, is accordingly used to calculate the power, P, used in the machine, as follows:

$$P_i = SSP_i \times Q_i \, .$$

This approach provides manufacturing decision makers with information on the total electricity requirements of each production machine, while SSP can be used to measure central pump/compressor system efficiency.

4.3.4 Showing decision makers the environmental consequences of a particular decision

It is proposed that LCA methodology be used to quantify the environmental consequences of production line material losses and energy use. The DES model is then used for calculating how system configuration changes affect production line material losses and energy use. Fig. 9 illustrates a third connection, the one between manufacturing decision makers and production line configuration.

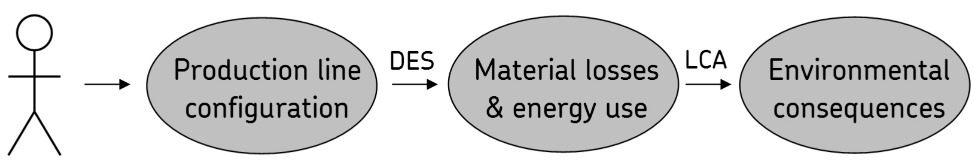

Fig. 9. *How manufacturing decision makers can be related to environmental consequences.*

The DES model includes a set of production parameters that can be varied to change the production line configuration. To investigate how a specific manufacturing decision maker, such as a machine operator, can influence the environmental performance of the manufacturing system, simulation parameters are selected based on whether machine operators have the power to influence them. By performing a sensitivity analysis of these parameters, it is possible to distinguish the most critical parameters (i.e., hotspots) for machine operators. Results from such analysis in paper II show that machine operators should specifically consider cycle time, power and compressed air demand, and setup time of the machines to control and/or improve the environmental performance of the manufacturing system. The same analysis can be performed for other manufacturing decision makers, such as those responsible for resetting, maintenance or process development.

5. DISCUSSION OF METHODOLOGICAL PROPOSALS

The aim of developing methods to allow manufacturing decision makers to understand the environmental consequences of their actions has been addressed by the three methodological proposals described in the previous section. The advantages and disadvantages of these proposals are discussed below.

5.1 RELATING LCA RESULTS TO AN ACTOR IN THE PRODUCT LIFE CYCLE

Presenting LCA results in a way that relates environmental consequences to a specific industrial actor, as in Fig. 5, clearly reduces the risk that receivers of the results will be discouraged from improving their environmental performance, since all environmental consequences are explicitly related to their activities. This method also allows for establishing parameters, based on life-cycle thinking, which may be used for continuous monitoring of the environmental performance of the manufacturing system. However, if the analyst can formulate and calculate relevant scenarios, these could be applied to an ordinary contribution analysis divided by life cycle stages, such as in Fig. 4. Like the proposed method, such scenarios would relate an actor's manufacturing processes directly to emissions and raw material inputs in other parts of the life cycle. In this case, the decision maker is also able to see where the actual change of environmental consequences is situated.

5.2 MANUFACTURING ENVIRONMENTAL PERFORMANCE

The proposed method to measure the environmental performance of an industrial actor's manufacturing system, as shown in Fig. 6 and Fig. 7, is intended to complement the conventional LCA focus on the product. It has the advantage of displaying the current manufacturing system's environmental performance from a life-cycle perspective. This means that the environmental consequences are related to an actor's *own* manufacturing processes and that similar consequences, such as CO_2 emissions stemming from different causes in manufacturing, such as energy use and material losses, can be compared on the same scale. This can help decision makers find possible improvements in the manufacturing system and set relevant action priorities based on environmental consequences. Since the method specifically focuses on manufacturing, it can be applied by a company to internally benchmark the life-cycle environmental performance of manufacturing sites. The method also concentrates on the environmental impact that manufacturing decision makers can actually do something about. However, the actual decision domain of decision makers in manufacturing can be larger or smaller than what is captured when measuring the environmental performance of the company's manufacturing processes in the suggested manner.

For example, it is clear that there are cases when manufacturing decision makers, such as those responsible for manufacturing development, influence more than just material losses and energy use in manufacturing. A new production method, for example, may change the product design constraints, which in turn may influence material choices and product performance in application. Other examples of manufacturing decision makers influencing more than what is covered by the proposed method are those responsible for direct material sourcing (e.g., when selecting component suppliers) and those working on quality control (e.g., when ensuring product longevity).

A weaker power to influence is retained, for example, by the decision makers involved in running production, such as machine operators and maintenance and resetting teams. The amount of material machined away from workpieces depends on product and process design, so the environmental impact of this material loss is largely outside the decision domain of these decision makers. Environmental consequences from the surplus material that is supplied just to be machined away when manufacturing the final product, however, is highly relevant to other manufacturing decision makers, such as those in manufacturing development.

However, when taking a step away from the conventional life-cycle perspective, as proposed here, and delimiting the analysis to material losses and energy use in the actor's manufacturing system introduces the risk of sub-optimization. Say, for example, that a new component is designed using an alternative choice of material of which the production is more CO_2 intensive than the production of the previous component and material; at the same time, however, the new component design and material reduce material losses in the actor's manufacturing system to almost zero. This would result in reduced CO_2 emissions related to the actor's manufacturing system but increased total CO_2 emissions for the material in the finished product. The same results may occur, even without changes in product design, in the case of outsourcing manufacturing processes. It must therefore be emphasized that the suggested method is not intended to replace ordinary life-cycle environmental assessment of the product, but to complement it.

5.3 DES AND LCA TO INVESTIGATE MANUFACTURING DECISION MAKERS' INFLUENCE ON MANUFACTURING ENVIRONMENTAL PERFORMANCE

The dynamic characteristics of a manufacturing system can be imitated using DES, allowing the calculation of energy use and material losses, based on what-if scenarios in which production parameters, that change system configuration, are varied. These energy use and material losses can be translated to environmental consequences using LCA methodology. By identifying the simulation model parameters that a specific set of manufacturing decision makers than can influence, the DES-LCA method can investigate how these manufacturing decision makers influence manufacturing environmental performance. However, as several authors have highlighted [72-76], one major barrier to running a DES project in industry is the time required for data collection. The data requirements of DES modelling alone are high, and they are increased by adding the environmental perspective by including material losses and energy use. Of the 6818 input parameters of the model produced in the case study included in paper II, 1113 were related to environmental modelling. However, many of the additional data may already have been collected for other purposes in the company, such as production energy management. Even more work is required if the LCA factors for the upstream environmental consequences of material losses and energy use, as well as the consequences of treating manufacturing residues, are unavailable. Without these factors, the analysis may still be done, accounting only for the amount and type of in-house material losses and energy use, but at the cost of losing the life-cycle perspective. The LCA-data required to develop LCA-factors may, however, be required for other purposes in the company. This information is required for quantitative benchmarking of suppliers' environmental performance or disclosing environmental data on the product to customers and other stakeholders.

6. DISCUSSION OF FURTHER RESEARCH

This thesis concludes by discussing some of the issues that may be productively addressed in further research, starting with the tasks most closely related to those carried out in this project, followed by issues more generally related to the broader field of research.

6.1 IMMEDIATE ISSUES

In the case study in paper II, machine operators were chosen to exemplify how decision makers can be related to environmental consequences. Performing the same analysis of other manufacturing decision makers remains to be done, such as those responsible for resetting, maintenance, process development or management.

For the test simulations in the case study in paper II, the relationship between model parameters and decision makers, exemplified by machine operators, was assumed. To investigate to what extent different manufacturing decision makers influence environmental performance, this assumption needs further investigation, first by investigating the parameters that different decision makers can influence, and then by investigating the range in which these parameters can be varied by each decision maker.

The model presented in paper II uses machine cycle time as an experimental factor. To investigate improvement potentials more thoroughly, cycle time may be divided between engagement and non-engagement time, such as loading and unloading. To increase the relevance to manufacturing decision makers, it has been suggested that the model be extended to modelling scrap rate as a function of engagement time.

6.2 BROADER RESEARCH ISSUES

In the background material section of this thesis, it is suggested that the existing decision support methods and the tools needed to assess the environmental life-cycle need to be further developed if they are to provide more effective support for manufacturing decision makers. An idea for accomplishing this has been developed into a formal method in this work. The relevance of the idea itself was not evaluated before carrying out the case study. More specifically, we have not discussed or investigated when and how production simulation is currently being used by manufacturing decision makers. When investigating this matter, it would also be useful to consider where in the current business process environmental assessment would be most suitable, in general, not only considering production simulation.

This research is developing ways to predict the environmental consequences of corporate decision making. We have made a link extending from the decision maker, through the manufacturing system, material losses, and energy use, ending with the resulting consequences for the environment. However to fully implement environmental considerations in business, it is also essential to find out how the proposed environmental benefit affects business values such as competitiveness, costs and investment returns.

Porter and Van der Linde [16] have identified a number of win–win situations in which environmental innovations have led to business advantages. There are, however, situations in which the investment cost for improving the environmental performance of the manufacturing system is larger than the immediate returns – seemingly a win–lose situation. However, even in this situation, it can sometimes be worth considering the risks and/or opportunities for a given investment on a longer term basis, especially if these business risks and/or opportunities are related to all the relevant stakeholders, rather than just current customers.

More research is needed to allow manufacturing decision makers to assess the *business* consequences of a decision that will change the *environmental* performance of a process for which they are responsible.

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