THESIS FOR THE DEGREE OF DOCTOR OF PHILOSOPHY

The green engineer

as an enabler of life-cycle management in manufacturing: models and practices

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Environmental Systems Analysis
CHALMERS UNIVERSITY OF TECHNOLOGY
Göteborg, Sweden, 2012

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ABSTRACT

The last 20 years corporate environmental management has developed from pollution control and emission prevention, to include a greater responsibility for indirect environmental issues along the whole product life cycle. This thesis aims at providing a better understanding of how such *environmental life-cycle management* can be applied on manufacturing processes. Previous environmental management research has argued for the integration environmental work in daily operations. This thesis investigates how the production engineers in the operational core of the organization may better understand and take action to reduce the life-cycle environmental impact of manufacturing processes.

Through the use of both practice studies and life-cycle assessment (LCA) method development, two research questions are explored; regarding (1) how the LCA methodology can be adapted for producing results that make sense to engineers in manufacturing, and (2) what is influencing production engineers to consider environmental aspects in their daily work.

The conventional product-centred LCA methodology is redefined to capture the environmental performance of a manufacturing process. The approach takes into account the power of influence of production engineers, and produce results that are related to the production processes of a company. The LCA method is combined with discrete-event simulation (DES) to identify technical improvement potentials in the manufacturing system. The proposed LCA-DES method offers the possibility to recognize, for a particular work role in manufacturing, the most significant factors influencing the environmental performance of manufacturing processes.

From the practice studies a wider organizational perspective is applied. The analysis unfolds the challenges of a transition from facility-oriented environmental management to life-cycle management in manufacturing. First, the prevailing understanding that it is preferable with a co-management of several issues, leading to an "integration" of various management systems, for environmental management is challenged. Second, a need of distinguishing between *direct* and *indirect* emissions in environmental management in

manufacturing is identified. The work to reduce indirect impacts of manufacturing operations need to be driven by manufacturing and engineering managers and thus be included in the normal work of improving the technical performance of the manufacturing process.

The thesis presents a model to understand why socio-technical factors become either a barrier or driver for the engineers to include environmental aspects in their work. It includes organizational factors, similar to earlier literature, but sees them from the perspective of the individual engineer, instead of as abstract factors, applied to describe the whole system, or organization. The proposed decision making model describes the driving force of environmental work as residing in the interplay of these factors. It is the situational interaction of several factors that determine action by the engineers and thereby also the environmental life-cycle work in the company.

KEYWORDS: practice studies; operation management; environmental management; life-cycle assessment; decision making; discrete-event simulation

LIST OF PUBLICATIONS

PAPERS INCLUDED IN THE THESIS

Paper I: Löfgren, B., Tillman, A.-M. & Rinde, B. 2011. *Manufacturing actor's LCA*. Journal of Cleaner Production, 19(17-18), 2025–2033.

Paper II: Löfgren, B., & Tillman, A.-M. 2011. *Relating manufacturing system configuration to life-cycle environmental performance: discrete-event simulation supplemented with LCA*. Journal of Cleaner Production, 19(17-18), 2015–2024.

Paper III: Baumann, H., Berlin, J., Brunklaus, B., Löfgren, B., & Tillman, A. 2011. The usefulness of an Actor's Perspective in LCA. In M. Finkbeiner (Ed.), *Towards Life Cycle Sustainability Management*, 73–83. Dordrecht: Springer Netherlands.

Paper IV: Löfgren, B. & Kokk, G. *In search of appropriate conditions for 'green' production engineering: lessons from the field.* Manuscript intended for journal in the field of operations management.

Paper V: Löfgren, B., Tillman, A.-M. & Kokk, G. *The practice of environmental life-cycle management in manufacturing: roles and responsibilities.* Manuscript intended for journal in the field of industrial ecology.

OTHER PUBLICATIONS BY THE AUTHOR

Löfgren, B. 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.

Löfgren, B. 2009. Capturing the life cycle environmental performance of a company's manufacturing system. Chalmers University of Technology.

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1 INTRODUCTION

The anthropogenically induced effects on our planet's ecosystem are alarming. In a well cited research paper (Rockström et al. 2009) nine planetary boundaries are defined "that must not be transgressed" in order for humanity not to provoke irreversible environmental change. The analysis shows that we have already passed the "safe operating space" for three of the boundaries. The critical state of the environment has been on the international political agenda, at least, since the first major conference on international environmental issues, the United Nations Conference on the Human Environment, was held in Stockholm in 1972. More recently, the fifth Global Environment Outlook report (UNEP 2012), prepared by the united nations environmental program (UNEP) secretariat, conclude that

> the currently observed changes to the Earth System are unprecedented in human history. Efforts to slow the rate or extent of change – including enhanced resource efficiency and mitigation measures – have resulted in moderate successes but have not succeeded in reversing adverse environmental changes. Neither the scope of these nor their speed has abated in the past five years (Ibid, p.6).

Manufacturing companies need to respond to this challenge in to ways. On the one hand, they need to innovate products with radically improved environmental performance, and on the other, they need to dramatically reduce the negative environmental consequences of production of goods (European Commission 2011). This thesis contributes to the latter. Drawing from three earlier publications (Papers I-III) and two manuscripts (Papers IV-V) I center my discussion on the engineering roles in manufacturing and how they may enable a transition from facility-oriented environmental management to environmental life-cycle management (LCM) in manufacturing.

2 BACKGROUND

2.1 AN EMERGENT TRANSITION TO ENVIRONMENTAL LCM

The traditional industrial environmental management perspective is centered on production facilities. For many years, environmental management in manufacturing 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 (Atwood et al. 1977; Bower et al. 1973; Pailthorp 1977; Russell 1971).

However, over the last 20 years the development has been from pollution control and emission prevention, to include a greater responsibility for indirect environmental issues along the whole product chain. The idea to shift from a facility–oriented perspective in corporate environmental management is not new. It has been referred to as the next logical step following the pollution control corporate policies (Hart 1995). Currently, the product life-cycle perspective is evident in broader political directions as Sustainable Consumption and Production in Europe (European Commission 2012b), partnerships as the UNEP/SETAC Life Cycle Initiative (UNEP/SETAC 2012), and European regulations as the Ecodesign directive (European Commission 2012a) and the producer responsibility principle of the WEEE directive (European Commission 2012c). Life-cycle consideration is a key element in industrial initiatives as the Greenhouse Gas Protocol (Ranganathan et al. 2004), and is apparent on the agendas of influential NGOs, expressed through for example the World Wildlife Foundation's partnership program Climate Savers (WWF Global 2012). Finding ways to manage this responsibility in industrial operations is thus increasingly important for businesses, a task that is sometimes referred to as environmental life-cycle management (LCM) (Baumann & Tillman 2004; Remmen 2007).

2.2 LCM IN MANUFACTURING: A CHALLENGE BEYOND BEING LEGAL COMPLIANT

In environmental LCM in manufacturing, the environmental performance of manufacturing processes are viewed, not in isolation, but encompassing consequences upstream and downstream in the product chain, beyond the vicinity of the factory area. The arguments for adopting such responsibility are largely ethical; it is reasonable to take responsibility for consequences of your actions, even though these do not directly influence you or your backyard. Indeed, many manufacturing companies today acknowledge that their production processes result in consequences for the natural environment, and increasing numbers of manufacturers are addressing these consequences, no matter where in the product value chain these occur. However, in many ways the facility-oriented perspective is still predominant in manufacturing environmental management practices (Lewandowska et al. 2012).

This is evident in the environmental strategies that multinational companies, based in countries with more stringent environmental regulations, had started to develop in the early 1990s (UNCTAD 1993). The environmental management systems that started to appear, intended to control and structure efforts related to the company's environmental impact. Most prominent were the introduction of the ISO 14000 environmental management system standards in 1996 and the EMAS environmental management system standards in 1995. While the adoption of environmental management systems can be related to legal pressure, the extent to which some companies attempt to reduce their environmental impact goes beyond being legally compliant (Prakash 2001). The way industrial actors take responsibility for the environmental life-cycle consequences of their manufacturing activities is an example of this. The *indirect* environmental emissions of manufacturing processes are inherently difficult to regulate by authorities. As an example, the direct sources of indirect CO_2 emissions from production of steel, are not necessarily located within the same jurisdictional area as the manufacturing process that is causing material loss, e.g. in terms of a scrapped steel component.

Reasons for voluntary industrial environmental initiatives have been explained as a response to external pressures exerted on the company (Darnall 2003). Plaza-Úbeda et al. (2009) argues that managers in "beyond compliance companies" believe that improved environmental performance also results in financial rewards. Others point at the ethical motives behind pro-environmental industrial action, namely that managers consider the environment simply because they believe it is "the right thing to do" (Bansal & Roth 2000, p.718).

2.3 USING CERTIFIED ENVIRONMENTAL MANAGEMENT SYSTEMS

Given that senior executive management in a large company has environmental life-cycle ambitions, it is a managerial challenge to realize these in the work practice of the company's sub-organizations. In a situation where a central (top-down) initiative is driving the organization beyond legal compliance, the external regulatory pressure supporting implementation is reduced. Without legally induced pressure it becomes important for advocates of the green initiative to communicate economical benefits of the initiative to business managers in the sub-organizations (Cordano et al. 2000). By adopting a third-party certified environmental management standard, for example ISO 14001 (Guler et al. 2002), external pressure and the formulation of business reasons for green actions can be reinforced (or re-introduced). The certification exposes the organization to external auditing at the same time as it provides reputation benefits (Potoski & Prakash 2005b).

Many studies (Corbett & Russo 2001; Florida & Davison 2001; Kollman & Prakash 2002; Montabon et al. 2000) demonstrate an improved competitive advantage from using environmental management systems (Heras-Saizarbitoria et al. 2011). Other studies give a more ambivalent picture of environmental management systems' effectiveness (Curkovic & Sroufe 2011). In general, these management systems and related certifications are intended to support a more effective running of operations. Several studies point accordingly at an increased environmental performance resulting from the use of environmental management systems (Johnstone et al. 2004; Szymanski & Tiwari 2004; Potoski & Prakash 2005a; King et al. 2005; Zeng et al. 2005; Montabon et al. 2000; Pan 2003; Russo 2009; Link & Naveh 2006; Rondinelli & Vastag 2000).

However, using certified management standards to drive environmental life-cycle strategies in an organization is not an obvious option. The most commonly applied environmental management standards have, since their introduction, been criticized for not taking into account the environmental life-cycle consequences of operations (Ardente et al. 2006; Ammenberg & Sundin 2005). No widely applied management standard provides equivalent means for implementing environmental life-cycle initiatives as ISO 14001 does with facility related environmental concerns (Jørgensen 2007).

2.4 Using operational technical core for environmental management

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 (Sarkis 2001; Simpson & Samson 2010; Gupta 1995; Boiral 2005; Hanna et al. 2000) that this responsibility structure is not suited for supporting effective environmental strategies in a manufacturing company. Parallel to the development of environmental management standards, methods for environmental improvement of the manufacturing system were suggested as a more operative counterpart to the environmental management systems (Bhushan, 1993; Borri and Boccaletti, 1995; Carley et al., 1996; GEMI, 1993; Hemenway and Hale, 1996; Miller, 1996). These proposed methods were inspired by the total quality management concept, where one of the fundamental aspects was the involvement of *everyone* in the quality management process, rather that only those working in the quality department (Miller 1996). Yet, the practical difficulty of integrating environmental considerations in day-to-day work practice is recognized in previous studies (de Burgos Jiménez & Céspedes Lorente 2001; Handfield et al. 1997; Angell & Klassen 1999) as well as in the popular business press (GreenBiz 2010). This is mirrored by a senior manufacturing manager, at one of the case factories of this thesis, who expressed with frustration that environmental issues are being handled "on the side, separately… in separate 'silos', disconnected from the day-to-day work in the organization" (Paper V).

A well recognized field of literature (new institutional theory) explains this phenomenon by saying that corporate behavior is determined by stakeholder's expectations. Organizations depend on support from different types of stakeholders and their willingness to exchange money, goods, services or people with the organization. In order to survive, organizations must conform to values and norms of their stakeholders even if conforming to such values and norms do not improve the organizations' efficiency (Meyer & Rowan 1977; Zucker 1987; Tolbert & Zucker 1983). To conform to diverse stakeholder expectations, without disturbing the operational technical core, organizations tend to separate "symbolic" and "substantive" actions (George et al. 2006) in different parts of the organization. For example, external pressure regarding environmental issues causes companies to create an environmental department that can contain environmental activities without disturbing core activities. However, while this and other literature explains why *organizations* act in certain ways (e.g. Bansal & Penner 2002) and thus informing policy makers about how to stimulate the greening of organizations, it provides less support to understand the lower organizational level that is closer to the operational core of the organization.

Several studies discussing determinants for corporate environmental initiatives distinguish *internal* factors from factors that are *external* to the firm (Weber 1997; Walker et al. 2008; del Río González 2009; Murillo-Luna et al. 2011). Walker et al. (2008) argue that, while the *drivers* of green supply chain management practices tend to be mostly external to the firm, while *barriers* are both internal and external. Murillo-Luna et al. (2011) reach a similar conclusion in a survey-based study of 240 Spanish firms. Barriers for advancing proactive environmental strategies are both external and internal, but "the difficulties that can actually prevent firms from progressing in their environmental strategy are within the firm" (ibid. 1424), i.e., internal. This supports the view that to gain a deeper understanding of the determinants of environmental work in organizations we need to look *within* firms. For a manager who is asking "What can I do to stimulate green actions in my organization?" the key is to understand why individuals in different work roles take green actions or refrain from taking such action.

2.5 ANALYSIS ON THE LEVEL OF INDIVIDUAL DECISION MAKERS

The influence on environmental management practice by other work functions, other than top-management, has been investigated from several perspectives. For example, by shifting research attention to middle and lower management levels Klassen (2001) finds that production plants where factory managers have a perception of a long-term viability of their operations and are driven also by ethical values (alongside financial performance criteria), have better environmental performance. Carter and Dresner's (2001) study the drivers and barriers to successful and unsuccessful environmental projects, specifically focusing on the role of purchasing. Several studies discuss the importance of, not roles but single *individuals* who act as environmental champions within the firm (Andersson & Bateman 2000; Egri & Herman 2000; Sharma 2000). Gattiker and Carter (2010) study successful strategies for environmental champions, represented by environmental management coordinators, to convince others in the organization to work with environmental projects. Verhulst and Boks' (2012) study on barriers among individuals for environmental initiatives in the company show that resistance is primarily related to the change itself rather than to the subject of change. Daily et al. (2012) demonstrated via a survey study the relationship between increased environmental performance, and environmental training of, and teamwork among, employees.

In the field of policy studies, individuals' decision making process have been of special interest. An overview of different decision making models is given by Wilson & Dowlatabadi (2007). Kollmuss & Agyeman (2002) explain the relationship between the possession of environmental knowledge and environmental awareness, and pro-environmental behavior. They distinguish between demographic factors (i.e. gender and years of education), external factors (e.g. institutional, economic social and cultural factors) and internal factors (e.g. motivation, environmental knowledge, awareness, values, attitudes, emotion, locus of control, responsibilities and priorities). However, these models are based on consumers, or private persons, and do not alone provide enough understanding of the factors influencing professionals, individuals within companies, in technical non-managerial roles.

2.6 USING LIFE-CYCLE ASSESSMENT FOR AWARENESS

One method recognized for driving environmental awareness and knowledge creation in industry is LCA (Baumann, 1998). Since its standardization process in the 1990s (Finkbeiner 2012), LCA has developed to be a central methodology for evaluating environmental impacts along product value chains. This has encouraged new business practices and introduced new responsibilities for companies and their functions (Heiskanen, 2002).

In the LCA procedure, a life-cycle model of the product is constructed, and the inputs and outputs of each process in the model are quantified and calculated as either resource use or emissions in the product life cycle. These inputs and outputs are interpreted as potential impacts on the environment. Extensive efforts have been put on adopting and/or redefining the LCA methodology for being applied for different purposes. In a corporate setting it can be used for decision making (e.g., product design and development) or communication (e.g., asserting environmental product claims). Recently an, almost overwhelmingly, detailed manual on LCA was released by the European commission's joint research centre. It is specifically taking the perspective of the application areas of LCA (JRC European Commission 2010), however the perspective of manufacturing decision makers is absent.

Even though the present mainstream LCA methodology is done from the perspective of the products, it provides an interesting framework for understanding the life-cycle environmental impacts that can said to be the environmental consequences of a *manufacturing process*. Such a definition would apply to those working to increase the performance of the manufacturing processes, enabling them to relate their actions to consequences for the environment. This is important for environmental management in manufacturing since the environmental impact from production processes is interlinked with technical performance (Sarkis 2001). The amount, and type, of material and energy that is used result in direct and indirect environmental impacts. In an industrial plant setting, engineering roles in production are thus key to reducing the environment impact of manufacturing processes. Their daily work concerns improvements regarding either the operation of current manufacturing processes, or the technical configuration of the system. Related thinking has been applied in a new field of LCA, that include in the analysis, the influence that different actors in the product value chain have on the energy and material flows (Brunklaus et al. 2010; Berlin et al. 2008; Kaenzig et al. 2011). This has been proposed for assessing manufacturing processes (Baumann & Tillman 2004, p.195), but never thoroughly investigated.

3 PURPOSE AND SCOPE

This thesis aims at providing operations managers in large companies a better understanding of how environmental life-cycle considerations can be included in their organizations. Considering that environmental LCM initiatives are beyond legal compliance, that certified environmental management systems provide less support, and the need of integrating environmental work in operations, I investigate how the engineers may better *understand* and *take action* to reduce the life-cycle environmental impact of manufacturing processes. Through both practice studies and life-cycle assessment (LCA) method development, I explore two research questions; first regarding,

> *taking action*: What is influencing engineers in manufacturing to consider environmental aspects in their daily work? (Paper IV and V)
>
> and second concerning, *understanding*: How can the LCA methodology be adapted for producing results that make sense to engineers in manufacturing? (Paper I, II, and III)

This thesis is the result of a collaborative project between the university and a manufacturing company, hereafter referred to as “the Group”. The aim of the Group management was to use our findings to improve the efficiency of the organization’s environmental work, in particular concerning the implementation of a life-cycle perspective.

3.1 A NOTE ON THE SCOPE OF THE THESIS

Targeting the challenge of reducing the environmental impact of *manufacturing processes* I focus on the production engineering roles in this thesis. The improved environmental performance of the products, by wiser design, and selection of materials, is essential for the company. In that challenge the design engineers play important roles, however the product design is not the scope here. To distinguish the environmental performance of a company’s manufacturing processes from that of their product, I assume that the product design is unaltered. The environmental challenge for the production engineers, and others, are to transform and assemble components and other materials in a way that is as environmentally benign as possible. The production engineering roles are not the only work role influencing these processes, however, they have been my centre of attention.

3.2 THESIS OUTLINE

The thesis is structured as follows. In section 4, I describe the multi-disciplinary, mixed-method, research approach, applied to contribute to the real-world challenge targeted in the research aim. The section includes method descriptions regarding both my practice studies and the LCA method development studies.

The result part of the thesis is divided in two sections. In section 0, I describe why engineering roles are increasingly important for manufacturing environmental management. We find that the organizational roles and responsibilities are different for the management of direct and indirect environmental impacts (Paper V), and that this is a challenge in the transition from a facility-focused environmental management organization to LCM in manufacturing. It is evident that engineering roles are especially important for considering indirect environmental impacts, which is the characterizing element of LCM in manufacturing. In the continuation of the section I use March & Olsen's logic of appropriateness (March & Olsen 1989) as a basis for understanding decision making. I propose a socio-technical framework to distinguish between engineering work practice situations that are more favorable for taking actions considering green aspects, from those that are or less (Paper IV).

I also investigate in section 6 how the conventional product perspective in the LCA methodology can be complemented with a manufacturing process perspective (Papers I & III). By drawing the technical boundaries in the product life-cycle based on what engineers in manufacturing are able to influence, we propose a definition of the manufacturing process' environmental performance. Furthermore, by using a conventional engineering tool, I demonstrate how the LCA methodology can be further adapted to single out the most important environmental aspects for a technical work role in manufacturing (Paper II).

The thesis concludes by discussing proposals in relation to research questions and previous literature, as well as, giving implications for practice. Summaries of appended papers in the thesis are given in an appendix.

4 METHOD

The conducted studies had an interventionist agenda (Jönsson 2010). Management at the Group wanted to improve the efficiency of the environmental work in the organization. This practice oriented goal was in line with my dual research objective: to tap into practical knowledge in order to generate theory as well as to translate the derived knowledge into solutions that are practically useful. As part of the interventionist approach, and as an additional way to "test" and get feedback on tentative conceptual structures, a reference group was assembled two to three times yearly throughout the process. The reference group, consisting of equal parts academic and industrial representatives, was used to reflect upon observations, data, models and draft texts. The industrial members (senior executives at the Group) of the reference group also functioned as primary informants, and supported the authors' understanding of company specific issues, as for example organizational structure and terminology.

The two research questions were explored using two separate case studies. The case studies applied different research methods, as described below. Both studies, however, benefited from the organizational access that included relatively free admittance to a broad range of internal documents (e.g., presentations, process templates, and other documents from for example the environmental management system) foremost via the Group's corporate intranet and databases. For the LCA method development case, this access included detailed measurement data on all separate machines included in the case production line, statistical production data, as well as data collection at suppliers of the Group.

4.1 PRACTICE STUDIES

The research presented in papers IV and V is the results of one field study at the Group. The longevity of the field study supported an iterative research process with a substantial overlap between data collection and analysis. When reviewing the literature and collecting data, categories, conceptual structures and tentative ideas emerged, which were modified, in a constant comparative approach (Glaser 1965), by additional data collection and literature studies. Eisenhardt (1989: 546-547) notes that such constant juxtaposition of conflicting realities tends to "unfreeze" thinking, and so the process has potential to reduce researcher bias when generating theory.

The triangulated field research design consisted of three activities that largely ran in parallel: interviewing, document studies, and participant observation. However, 44 semi-structured interviews, with an average length of about one and a half hour, comprise the main empirical base. The interviews were audio-recorded and transcribed verbatim; after which respondents validated and confirmed the transcripts. Of the 44 respondents 21 are white-collar technical personnel in either of two factories at one of the production site of the case-company: twelve work as process development engineers and nine as manufacturing engineers. The remaining 23 interviewees belong to either one of three categories: The first category consists of roles at factory level: one first-line production leader, two production managers, one production development manager, two EHS-coordinators (environmental & health-and-safety coordinators) of which each plant has one, two procurement engineers, two HR-representatives, one factory manager, one business developer, two financial controllers, one machine operator, and one purchaser. The second category consists of roles at the national level organization; one environmental manager, one central energy system engineer, and the general manager of the Group Sweden. The third category consists of roles at division level or Group level: the manufacturing director, three senior process development engineers. The views of this mixed group of respondents were valuable not only in order to get a better understanding of the industrial and factory setting where the engineers work, but also to learn how the work of engineers relates to adjacent organizational roles and how various stakeholders directly or indirectly influence the engineering work.

Beginning in 2009, most interviewing was done in 2010 and 2011. Identifying relevant interviewees and other data sources was done by theoretical sampling, an iterative sampling process aiming at developing a rich understanding of emerging theoretical concepts (Glaser & Strauss 1967), with an added component of snowball sampling. At some point we approached what we felt was theoretical saturation. Instead of using a standardized interview guide with a set of structured questions identical for each respondent, the “guide” was a semi-structured collection of topics and questions to be discussed with an aim of acquiring narratives rather than answers. From the narratives we elicited relevant conceptual categories and structures of categories. Topics and questions were modified depending on the organizational role of the interviewee, but also because later interviews were informed by conceptual relationships that were drawn and topics and questions that emerged from previous interviews, and from other conversations. This approach was enabled partly by the relatively drawn out interview phase, partly by the triangulation with other types of data collection, and partly by the continuous blurring and intertwining of data collection and theory building (ibid: 43). Although specific topics and questions changed somewhat over the course of the field study the general interview theme remained unaltered, i.e., the environmental work at the factories of the case-company, with special emphasis on day-to-day engineering work practice.

A daily presence in the organization over an extended time facilitated practitioners' input in the research process, e.g., by giving feedback on emerging theories. (M. Schultz & Hatch 2005), and sharpened the interpretative insight of the researcher—what Glaser (1978) calls theoretical sensitivity. As noted by Schultz and Hatch (2005: 344), "[f]ruitful interaction between research and practice requires a longitudinal relationship to experience first-hand the shifts and ongoing dynamics embedded in practical first-order constructs". The gained insights were documented in field notes and discussed in the research group. The participant observation element of the study, in combination with the use of a reference group, strengthened the construct validity (Yin 2003) of the study.

4.2 LCA METHOD DEVELOPMENT

Papers I and II are based on a practical LCA study at one of the Group's manufacturing sites. The study was done to explore the idea of doing an LCA that would support people working in manufacturing. It was done prior in time to the practice studies, described above..

The initial idea of the thesis project was to try and find ways to combine LCA with a production simulation method to increase the level of detail of the analysis and thus, assumingly, make it more relevant to people working in manufacturing. The case was thus designed to find a way to interpret inventory results from the perspective of manufacturing decision makers. Without knowing the well-defined problems for which the method may be used, the goal of the study was defined broadly, i.e. to investigate how manufacturing decision makers can influence the environmental performance of the manufacturing processes.

First, an LCA study was conducted for one of the Group's products. This initial cradle-to-gate study was conducted to identify the activities that caused the most environmental impact when manufacturing a product, specifically focusing on global warming potential. Part of the study was performed as a master's thesis project (Rinde 2008). Each machine and process was measured on site using portable measuring equipment and software that was specifically designed in collaboration with specialists at the Group for collecting data on electricity, compressed air and process fluids. Measuring techniques were developed, to allocate the energy use for pressurizing and distributing compressed air and process fluids to the machines, end-users of energy, in the production line (Löfgren 2007). The results were later extended to a full cradle-to-grave LCA model by using simplified modeling to account for greenhouse gas emissions attributable to the use phase and end-of-life of the product.

Based on the findings of this LCA study the research team (reference group members and I) discussed how the results could be formulated to better suit the information needs of decision makers in manufacturing. In an iterative process a proposal emerged on how to draw the system boundaries in a way suited to capture only the environmental performance of the manufacturing processes. This proposal was inspired by earlier LCA studies using an actors perspective (Brunklaus et al. 2010; Berlin et al. 2008).

LCA data collection was done in parallel to data collection for producing a discrete-event simulation (DES) model. The combined DES-LCA model was implemented in commercial DES software after finishing the initial LCA study. Additional data on a production line was collected on-site to capture all details of the production line. The conceptual model was validated to be "face valid", meaning that production line personnel confirmed its correspondence to reality (Robinson 2004). The computerized model was validated by comparing simulation results with actual production output, electricity use, and compressed air use; the validation period was six months of production. Due to lack of statistical records for other energy carriers, these were not validated.

It must be emphasized that the concrete assessment results of the LCA and the LCA-DES studies, described in detail in the papers (I and II), are not the main results of the research; rather, the studies were used in the process of refining the initial concept into a method.

5 ORGANIZATIONAL AND INDIVIDUAL ASPECTS INFLUENCING LCM IN MANUFACTURING

This section discusses two managerial challenges related to LCM in manufacturing. The first is to how adapt the environmental management in such a way that more of the environmental improvement work is put in the hand of operational managers and engineering roles in the technical core of the organization. The second is how to create appropriate conditions for the engineers to include environmental aspects in their work.

5.1 THE IMPORTANCE OF ENGINEERING ROLES FOR LCM IN MANUFACTURING

Paper V describes some of the organizational challenges resulting from a transition from a facility-focused environmental management to one including stronger life-cycle considerations. Since more than fifteen years the environmental work at the studied manufacturing site of the Group had been guided by a combined management system for environment, health, and safety (EHS). My research colleagues and I entered the factories six years after the company's launch of a new integrated business and environmental strategy that included strong elements of environmental life-cycle consideration. We met an organization frustrated about the organizing of environmental management. Activities intended to improve environmental performance were described as entering the organization "on the side, separately, as extras". Informally, responsibility for environmental matters largely belonged to EHS coordinators, in spite of that these formally have only a networking role. In the annual environmental assessments of production lines the EHS coordinator was driving the work, while formal responsibility resided with the factory sub-unit and production line managers.

In our analysis of the situation, we distuingished between the organization practices relating to *direct* environmental concerns from those that are *indirect.* Our understanding of direct and indirect environmental impacts was based on an LCA framework describing the physical system of energy and material flows (Paper I).

Earlier studies indicate that the introduction of environmental LCM practices is simplified if the organization first has embodied more basic environmental capabilities, such as preventing direct emissions (Hart 1995; Darnall 2003; Christmann 2000). The resources built using a certified environmental management system in our case were focused on abating direct emissions. We found how this competence is different to the qualities required for adopting an environmental life-cycle perspective in manufacturing.

First, the direct and indirect dimensions of the company's environmental impact are two very different issues, with differing capability requirements. Thus, environmental concerns cannot be treated as *one* of several aspects to manage in an integrated management system. At the manufacturing site most of the work that was done to reduce the environmental impact regarded direct emissions from factory operations. For these there were clear regulatory incentives to take action. In contrast, the driving force to reduce the life-cycle consequences of manufacturing processes (the indirect emissions) came from internal stakeholders, indeed from top-management. Customers exerted no influence in this respect. Neither did regulatory pressure from legal authorities nor environmental management system certification bodies. Furthermore, the actions required to improve the indirect environmental impacts were perceived to be more intertwined with what could be considered conventional performance parameters. The indirect environmental effects further up the value chain were related to the amount of energy and materials used in the factories. These were more related to costs than to issues regarding health and safety, or direct emissions from the factories. There is thus often a win-win situation, as regards cost reduction and improved environmental performance, for indirect environmental effects that is less prevalent in the work that is aiming at reducing direct emissions. This lead us to our first proposition regarding the adaptation of a life-cycle perspective in the environmental management in manufacturing:

> P1: Direct and indirect environmental issues are two different management aspects, which require different organizational approaches.

The second required capability change for life-cycle environmental concerns regard the roles in the environmental management systems. In the presence of regulatory pressures coordinating roles, such as EHS coordinators, may raise enough incentive to induce actions in the manufacturing line organization. However in absence of external pressure, work roles without formal decision power may prove insufficient to induce action. At the manufacturing site the union organizations were strong external stakeholders for continuously improving the work place. Direct emissions were in focus by local authorities. However, for the indirect emissions, a Union or legal counterpart was missing in the factory organizations. Without a similar external representative these issues are in larger need of being driven by people in the manufacturing line organization, with decision mandate. This leads us to propose that:

> P2: The indirect environmental impact is in larger need of being driven by people with mandate to approve changes and investments, than direct environmental or health and safety concerns.

Prior studies show that environmental actions are more likely when being managed in an integrated management system (Beechner & Kock 1997; Lawrence et al. 1998; Wilkinson & Dale 1999; Chinander 2001). Also, the aspects considered in ISO 14001 and the management system for occupational health and safety, OHSAS 18001, are favorable to combine due to the high compatibility of the two management systems (Sampaio et al. 2012). However, despite the systems' overlapping features, Salomone (2008) finds that one of the major obstacles with integrated management systems is the risk of "not attributing the right level of importance to each variable quality, environment, safety" (Ibid, p.1802). Our observations show support for the notion. We find that when co-managing environment and occupational health and safety, the health and safety issues receive most attention.

A clear concern was expressed about this by EHS personnel and by managers in the factory organizations. Environmental concerns, in general, had received additional attention in the organization with the new environmental strategy, and a number of actions had been taken centrally at the manufacturing site. To target indirect environmental issues, technical personnel were given new roles (as energy coordinators) and the personnel closest to the machines in the production lines were given energy training. However, at the time of the field study few technical improvement initiatives to reduce energy use had been taken in the factories. The focus was still new for the factories and the rareness concrete initiatives may be partly explained by a general resistance to change in organizations (Verhulst & Boks 2012). However, a contributing factor that is specific to environmental LCM, is evident in the case of the Group. In accordance to prior findings (Chinander 2001; Lewandowska 2011), environmental issues are generally considered less tangible than occupational health and safety issues. It is reasonable to believe that this perception is enhanced for indirect environmental impacts since they are even more distant to the decision maker than direct environmental impacts. The final proposition is that:

> P3: There is a risk that the co-management of environmental and occupational health and safety issues influences environmental life-cycle management in manufacturing negatively.

The observations illustrate the increased importance of including operational management and engineering roles in environmental management that include consideration of indirect environmental impacts.

5.2 Conditions for including environmental aspects in daily engineering work

To shed light on the circumstances surrounding green actions (or inactions) by production engineers we propose in paper IV a model for understanding what is hindering and supporting engineers working in a factory to include environmental considerations in their improvement work.

March and Olsen's (1989) seminal formulation of a logic of appropriateness offers a useful way of thinking about the action by any given work role. Mainstream environmental policy analysis usually assumes that behavior follows a rational action model (Lutzenhiser 1994; Wilson & Dowlatabadi 2007). In trying to see the world from a neutral and detached perspective, the decision-making of supposedly rational actors is based on calculation, intentionality and deliberate reflection on what is the most efficient means to achieve a certain end, such as reducing energy consumption. By contrast, if action is viewed as predominantly norm- and rule-based, it is conceived "as a matching of a situation to the demands of a position" (March & Olsen 1989, p.23). People uphold roles and identities that provide rules or scripts for appropriate behavior in different situations. Actors seek to fulfill the ethos, practices and expectations that come with a role, an identity, or with the membership of a group. The actor, embedded in a social collective or a network of social settings, follow rules if he or she perceives them as natural, rightful, expected and legitimate in the specific situation.

The logic of appropriateness encompasses two ideal modes of social action. On the one hand it deals with rules that are so thoroughly internalized that the actor takes them for granted, like habits. On the other hand it deals with a reflexive process whereby actors employ a conscious thought-process to make sense of what behavior is appropriate to a situation, before deciding how to act (ibid: 23). "The simple proposition of the logic of appropriateness is that, most of the time when humans take *reasoned* action they do so by trying to implicitly or explicitly answer the following questions: 'What kind of a person am I?', 'What kind of situation is this?' and 'What does a person such as I do in a situation such as this?' (ibid.). "The accountant asks: What does an accountant do in a situation such as this? The bureau chief asks: What does a bureau chief do in a situation such as this?" (ibid. p.24).

If we accept the view, the ontological perspective, that decisions and actions of individuals are based on questions about situational appropriateness, rather than on optimizing results and focusing consequences of actions, we need to seek understanding of what it is that shapes the rules of appropriateness that people in different work roles follow. Using this perspective we identify, in the empirical data, five overarching factors that influence the engineers in their decision making process: Organizational infrastructure, Technical system, Competence, Direct stakeholders, and Resources. The influencing factors should not be seen as objectively given or decidable, but rather as subjectively perceived (even the technical system) by the individual engineer.

- The *organizational infrastructure* includes the individual's perceptions of organizational charts, standard operating procedures, routines, tools, their own and others' work-roles and responsibilities, etcetera.
- The *technical system,* including (i) machinery and equipment, (i) direct and indirect materials, (iii) the physical structure of the production channels and factory buildings, and (iv) the rest of the product value-chain. The technical system (both in terms of the current system and possible improvements) is at the center of engineering work practice, and as such it clearly has a profound impact on the engineers' decision-making space. For engineers in the factories, the technical system simultaneously (a) is the subject matter of their work, and (b) sets the scene for what changes, and actions in general, are possible.
- *Competence,* Broadly defined, including (a) knowledge (knowing facts and methods), (b) skills (being able to do something), (c) perspectives, experiences, the ability to apply the knowledge in different frames and circumstances, and (d) personal values and attitudes.
- *Direct stakeholders*. A host of stakeholders (inside or outside the company) have a direct impact on how the individual engineer spends his or her time and effort. Immediate managers and internal customers have large influential power, but even the engineer's family, friends and memberships in other organizations may have direct influence on priorities and decisions in the work life.
- *Available resources* includes time, money and human resources: the *time* the employee perceives is available for working with different issues, based on his/her set of priorities, and the perceived resources in terms of *money* to spend or

invest in for example new and more energy efficient equipment. With human resources we mean the network of people around the engineer

Again using the case of the two factories of the Group, Paper IV describes the way engineers' viewed their working roles (or identity) and the situations of green action or inaction to identify the drivers and barriers behind the behaviour. The paper arrives at a model of factors that describes the socio-technical conditions wherein engineers make environmental decisions. These factors define the context of the cognitive decision making process of the individual, and is influencing what he/she perceives as his/her *identity*, the *situation* and corresponding *rules* to follow (see Fig. 1). In other words, the proposed model does not predict which action a particular engineer will take in a particular situation. From an appropriateness point of view, it depicts the conditions in which the engineer, implicitly or explicitly, is asking "What does an engineer such as I do in a situation like this?".

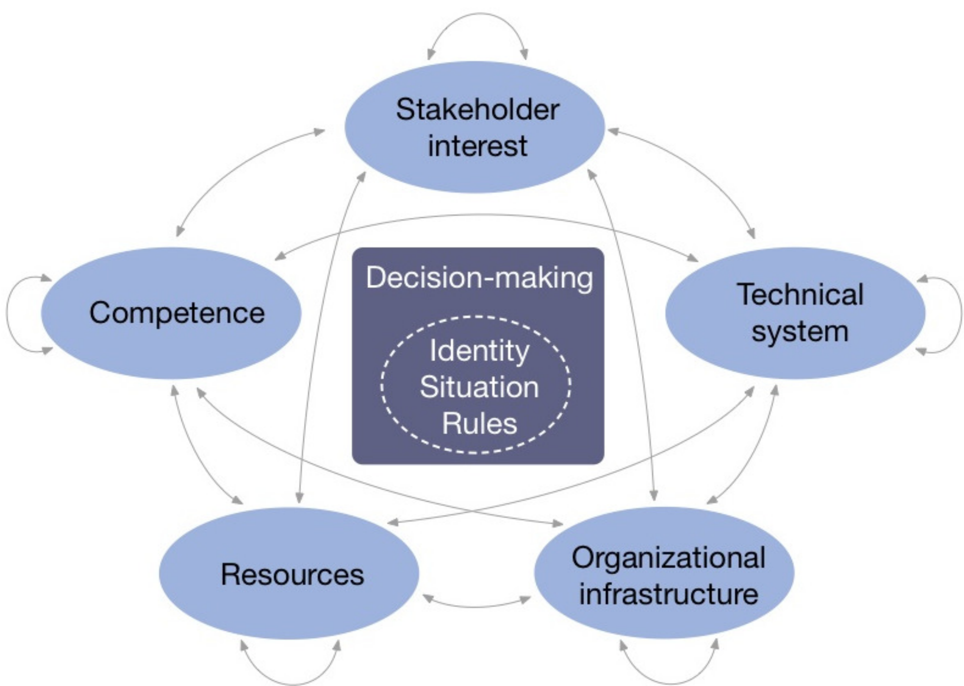

Fig. 1 The factors of influence. Arrows illustrate interrelationships of factors.

When respondents raise any issues that influence green practices, it is usually done in the form of short narratives that describe some kind of conflict, mismatch, and dissonance between the influencing factors. In the model the relation between different factors is depicted by arrows, e.g. there may be a conflict between the personal values (competence) of the engineer and his/her stakeholder interest. But elements within a single factor may also influence decision-making in different ways. For example, the influence exerted by the engineer's direct manager may be in dissonance with what the engineer perceives as priority in the new green business strategy. The empirical data in the case study included many conflicts, both between and, within factors, depending on the situations and individuals.

The model depicts dynamic conditions that are unique for each individual and for any given individual from one situation to another. To say which conflict is most important for including green aspects in decision making would thus require a deeper study following a limited number of individuals in a specific situation, like a project. Still, I posit that each one of the five influencing factors and their relation with other factors can be modified by management (possibly in cooperation with the engineers). The model thus provides a basis for the formulation of strategies to make environment a performance parameter in the technical improvement work.

6 MAKING SENSE OF THE LIFE-CYCLE ENVIRONMENTAL IMPACT USING LCA

The most recognized method for environmental assessment from a life-cycle perspective is life-cycle assessment (LCA). An important value of the analysis is its holistic scope, enabling the identification of potential environmental tradeoffs throughout the product chain. However the focus on the product in conventional LCA takes attention from the task of engineers that focus on the performance of the *manufacturing* processes. In two ways, the methodology does not relate environmental consequences to the parameters of decision making in manufacturing.

First, the method does not normally measure the environmental performance of manufacturing processes. The method was developed to shift the perspective of environmental analysis from production site to the product's life cycle. The initial industrial application of LCA was as a tool with which design engineers could environmentally optimize the product (Hunt & Franklin 1996), a concept that now has established itself as "design for the environment", which includes many more tools and methods than conventional LCA (see e.g. Mackenzie, 1997). The product focus has continued to dominate the development and application of LCA, and the option provided in ISO's LCA standard for assessing the environmental consequences of a service, such as a manufacturing process, are less investigated and used (Baumann & Tillman 2004).

Second, its holistic aims have made the LCA method rather low in resolution, being unable to consider, for example, the dynamic interrelationships between manufacturing processes, which are characterized by several subsequent, parallel, and conflicting processes that evolve and change over time. LCA is based on static calculation procedures, which are characteristic of current commercial LCA software. This section demonstrates how the LCA methodology can be adapted for results to make more sense for engineers working in manufacturing.

6.1 THE ENVIRONMENTAL PERFORMANCE OF A MANUFACTURING PROCESS

In LCA, the conventional way to identify the processes in a life cycle where improvement is most needed is 'dominance analysis' (Guinée 2002). This can be 'used by a company wanting to know whether they are at risk of exposure in the environmental debate or if it is their own production processes or those of their suppliers that cause the greatest problems' (Baumann & Tillman 2004). Apart from distinguishing between the small and large contributions of individual processes or groups of processes, this analysis method can be used to compare the contributions of arbitrarily chosen parts of a system, for example, various parts of a life cycle or product.

The holistic nature of LCA encourages the analyst to define very broad analytical goals, for example, what should be changed in a product life cycle to reduce global warming. However, doing so it is forgotten that no single decision maker can influence the whole life cycle of a product. Even when relevant decision makers are better defined, dominance analysis can be less informative when, for example, a company is aiming to improve the environmental performance of its manufacturing system. Dominance analysis is concerned more with accounting for the *parts* of the life cycle or *groups* of processes that dominate the environmental impact of a product than with considering the potential for specific actors along the product chain to improve the current situation.

The results of a dominance analysis do not directly reflect the relationship between processes and emissions or raw material inputs in other parts of the product life cycle. The analysis does not consider the root cause of why, for example, CO_2 is emitted from a process. Consequently, a decision maker might be discouraged to take action to improve their own processes in cases in which 'hotspots', i.e., processes contributing the most to environmental impact, seem to be located outside the decision domain of the decision maker (Heiskanen 2000). Moreover, the identified hotspots, from an analysis of the product's environmental performance, are not necessarily the processes where the company's decision makers have the greatest potential to improve environmental performance. Therefore, such hotspots may confuse rather than support decision makers in prioritizing actions.

In response to these deficiencies a new category of LCA methodologies have emerged considering, not the energy and material flows in isolation but also, the decision makers' influence in the product lifecycle (Paper III). At present the methodologies developed provide options for modeling LCAs to:

- identify to which extend the environmental impact is under an actor's control (Baumann & A.-M. Tillman 2004),
- divide LCA results by value chain actors rather than life-cycle phases/processes, and assessing best improvement action for each actor (Berlin et al. 2008),
- evaluating most influential actor (Brunklaus et al. 2010),
- evaluate the impact from actors' ability to put demand on other actors in the value chain (Brunklaus et al. 2010)
- understand how energy and material flows in a specific actor's processes relates to environmental consequences no matter where in the value chain they might occur (Paper I), and
- focus on the environmental consequences that a manufacturing actors in a certain company is able to influence (Paper I).

Paper I presents a way to use LCA for considering the environmental impacts from the manufacturing processes that a production engineer, working in a specific company, is able to influence. For this purpose it is assumed that product design remains unchanged. It is the manufacturing processes of transforming and assembling material are the focus rather than the product itself. The inefficient use of materials and energy in this process needs to be compensated for by additional material and energy use further along the supply chain. The total amount of additional energy and material used depends on where in the value chain these material losses occur and on the types of processing steps the material has passed through. As basis for the production engineers' understanding of the environmental aspects that requires action, the method link environmental system-level consequences to concrete aspects, root causes related to the manufacturing processes they work with.

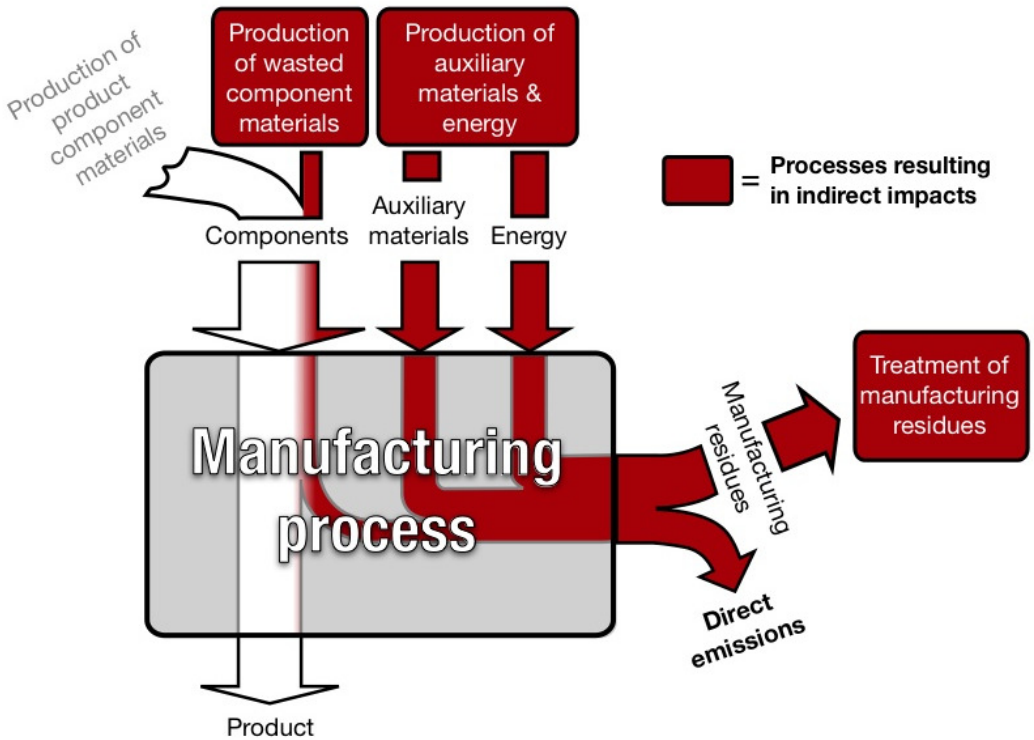

Fig. 2 The life cycle environmental impact of a manufacturing process. Adapted from Paper I.

When illustrating the environmental performance of the manufacturing process in Fig. 2 we distinguish between *direct* and *indirect* environmental impact. The environmental impact related to manufacturing processes is illustrated as the red/dark flows and processes. The direct environmental impacts constitute the emissions discharged from the manufacturing site itself. The indirect impacts occur when usage of material or energy at the manufacturing site causes emissions elsewhere, i.e., from suppliers' processes or from treating manufacturing residues. The part of the component materials entering the manufacturing process (white arrows in Fig. 2) which end up as part of the product are not regarded as part of the life-cycle impact of the manufacturing process. Formally, the production of the capital equipment used to transform or assemble the materials in the actor's manufacturing system should also be included, even though the effects of those are usually small in comparison.

The method offers a way of viewing the environmental performance of manufacturing processes which complements the important product life-cycle perspective in contemporary environmental management. However, in order to find improvement potentials a more detailed assessment might be appropriate. The next sub-section explores how this approach may be applied through using a conventional engineering tool.

6.2 THE ENVIRONMENTAL HOTSPOT FOR A TECHNICAL WORK ROLE

One method designed for evaluating the performance of manufacturing systems in detail is that of discrete-event simulation (DES). This simulation method was developed in computer science in the late 1970s to imitate the engineering of human-made systems (Zhou 1998). DES is event-driven simulation in which a real dynamic process is imitated throughout its progress in time. In the case of a manufacturing process, the process is mapped as the parameters (factors) that likely influence the objective function (response) under study. Such parameters may include machines, labor requirements, cycle times, resetting times and production hours. Together with statistical data on interventions, such as machine breakdowns, that may influence the response and the relationships between all these factors, the model can be implemented as a computer model. Current commercial DES software has been used for several applications apart from manufacturing, applications such as hospital planning, airport baggage system design, and shipping and delivery logistics (Lanner 2009). These are examples of systems in which DES allows the prediction of *system* performance, something which is not easily done using other modeling approaches. Furthermore, the value of DES has been said to lie in its ability to capture the *variability* of events instead of using mean values as model input, restricting the need for assumptions, and in its ability to provide transparent information for decision makers by means of animated graphic interfaces (Robinson 2004). Though DES was not specifically developed for environmental systems analysis, there are no theoretical reasons why it cannot be applied to them.

By combining LCA with DES we were able to directly relate life-cycle environmental consequences to detailed technical aspects of the manufacturing processes. Paper II presents a way of using a DES model for company's manufacturing processes and thus calculating energy use and material losses, which in turn are associated with environmental consequences, evaluated by means of LCA. The LCA-DES method can thus be applied to single out those aspects influenced by a specific work role that are most environmentally critical.

In a method development case study, a model including 6818 input parameters that can be varied as factors in a simulation run was developed. To explore how well the model captured the way manufacturing decision makers can influence the environmental performance of the company's manufacturing system, a number of these parameters were selected. In this case, this selection represented the factors that machine operators were assumed to be able to directly influence. However, any decision maker in the manufacturing system could be represented by a set of parameters that they influence.

The goal was set to distinguish the factors, in the decision domain of operators, which influence environmental performance the most, i.e. the hotspots. The factors that machine operators were assumed to be able to influence were:

1. machine mean time between failures,
2. machine cycle time,
3. machine compressed air demand,
4. machine power demand,
5. machine process fluid demand,
6. number of processed parts before manual cutting tool adjustments/change,
7. manual product quality control time,

8-9. machine ramp-up after setup (i.e. modeled as the two separate factors: machine output reduction and time to normal machine output)

10. machine setup time
11. effective cutting tool (e.g. inserts, honing stones, and grinding wheels) changing time per machine, and
12. scrap rate.

To gain a rough idea of how much the machine operators influence environmental performance, the factors were tested for sensitivity using a design of experiments approach with the commercial statistics software Minitab 15 (Minitab 2009).

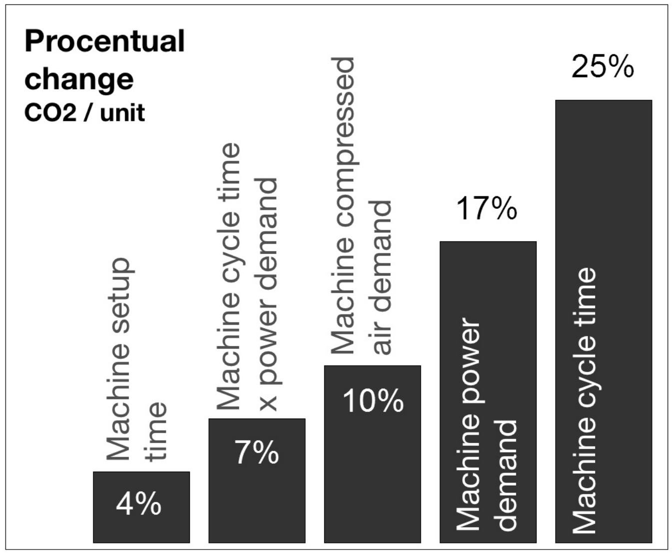

Fig. 3 Machine operator hotspot diagram. The figure displays the five most significant changes on lifecycle CO_2 emissions per unit of product. The result is the effect either of the change of a single factor or as the interaction effects of two factors. Adapted from Paper II.

As results from the simulation experiments Fig. 3 show the how sensitive the environmental performance (i.e. direct and indirect carbon dioxide emission equivalents per produced unit) was to a change (50% increase) of any of the factors that machine operators were assumed to be able to influence. For machine operators the most sensitive technical factors were machine cycle time (25% CO_2-eq increase), machine electric power demand (17% CO_2-eq increase), and machine compressed air demand (10% CO_2-eq increase). Thus for the machine operators working in this production line, the "hotspots", or the most critical "global warming performance" aspect is to ensure correct machine cycle time.

7 DISCUSSION AND CONCLUSION

This thesis has presented the results from explorative practice studies and LCA method development. So how do the results inform us regarding how production engineers may better *understand* and *take action* to reduce the life-cycle environmental impact of manufacturing processes? And how does this relate to previous knowledge?

7.1 LCA AS A MEAN FOR UNDERSTANDING ENVIRONMENTAL IMPACTS

In previous literature (Hasanbeigi et al. 2009; Rohdin & Thollander 2006) and underlying several of the factors in our decision making framework (Paper IV) the importance of being able to quantify and relate to environmental issues is fundamental for action. Targeting this need I show how the conventional product-centred LCA can be complemented, by redefining the LCA method to capture the environmental performance of a manufacturing process. This is done by viewing the manufacturing process as a service, namely the service given by the production processes when transforming and assembling components into finished products. The results enable manufacturing decision makers to identify improvement potentials in their spheres of influence. Energy use and material losses, together with the direct emissions in their manufacturing processes, are shown to be decisive parameters. The method reduces the risk of discouraging production engineers by identifying hotspots outside their domain of influence, by relating environmental consequences to causes in their manufacturing systems.

To further identify technical improvement potentials in the manufacturing system I have demonstrated how LCA can be combined with DES. This modeling approach offers a way to relate life-cycle environmental consequences to detailed changes in manufacturing system configuration. Contrary to how these two methodologies have been merged in previous work (Dietmair & Verl 2009; Heilala et al. 2008), I show that the method offers the possibility to identify the most significant factors influencing the environmental performance of manufacturing processes; those that individual work roles are able to influence. The example also illustrates how the manufacturing process adapted LCA method can be applied together with more conventional engineering tools.

While a company may use the proposed LCA methods for finding improvement potentials for manufacturing decision makers, the proposals also provide options for developing environmental performance indicators. Establishing performance indicators using LCA has been proposed (Hermann et al. 2007; Zobel et al. 2002) and applied (Perotto et al. 2008) in earlier studies; however, these authors use the more conventional cradle-to-grave system boundaries, and thus do not take into account the different perspectives in corporate environmental management. The categorization of the environmental impacts related to a manufacturing process in Fig. 2 as (1) direct emissions; and indirect emissions resulting from (2) production of wasted component materials, (3) production of auxiliary materials, (4) energy, and (5) treatment of manufacturing residues, serve as basis for the formulation of indicators capturing the life-cycle environmental performance of a company's manufacturing process.

7.2 CONDITIONS FOR ACTION ON DIRECT VS INDIRECT ENVIRONMENTAL ISSUES

The presented adaptation of the LCA methodology does not alone allow us to understand how environmental life-cycle considerations can be part of daily work in a manufacturing organization. By studying the practical challenges related to a transition to environmental management practices including environmental life-cycle aspects I have distinguished between organization practices related to their *direct* environmental concerns, from those that have *indirect* implications for the environment.

Exemplified by the introduction of new management standards (ISO Central Secretariat 2011; Bunse et al. 2011), and outlined in the background section of this thesis, corporate environmental management is increasingly directing attention to indirect emissions. Our study (Paper V) support the previously stated need of engaging the operational part of the organization in environmental improvement work (de Burgos Jiménez & Céspedes Lorente 2001; Handfield et al. 1997; Angell & Klassen 1999; GreenBiz 2010). However, we found that for environmental management in manufacturing this need is larger for targeting indirect emissions, than for direct emissions. The study also identifies the organizational difficulties related to implementing LCM practices in a combined management system for environment and occupational health and safety. We thereby challenge the prevailing understanding that the co-management of several issues leading to an "integration" of various management systems is preferable for environmental management (Zutshi & Sohal 2005; Jørgensen et al. 2006; Zeng et al. 2007; Fresner & Engelhardt 2004; Bernardo et al. 2010; Salomone 2008; Bernardo et al. 2009; Douglas & Glen 2000). This is because life-cycle management in manufacturing may be difficult to accomplish by modifying current certified environmental management systems, i.e., by extending it or combining it with other management systems. As long as life-cycle aspects of manufacturing remain outside the legal obligations of the factory, the management of these needs to be driven by manufacturing and engineering managers. Indirect environmental concerns thus need to be included in the normal work of improving the technical performance of the manufacturing process. Beyond compliance initiatives as the Greenhouse Gas Protocol (Ranganathan et al. 2004) and Climate Savers (WWF Global 2012) provides external pressure on the company as a whole, but the incentives are not automatically channelled to the local manufacturing organizations.

7.3 Conditions for action by engineers

Earlier studies on barriers and drivers for green practices in companies give valuable insights. The more detailed case studies (e.g. Rohdin & Thollander 2006) describe situations with case-specific barriers and drivers, and the survey-based studies using statistical methods (e.g. Murillo-Luna et al. 2011) describe the reasons behind green action in more general terms. Neither of these develops support for understand why a factor becomes either a barrier or driver for environmental improvement work. The model presented in section 5.2 adds this dimension to earlier work. It uses organizational factors, of which most are included in the discussion on barriers and drivers in earlier work. But we see them from the perspective of the individual engineer, instead of as abstract factors, applied to describe the whole system, or organization. The model presented here describes the driving force of environmental work as residing in the interplay of these factors. It is the situational interaction of several factors that determine action by the individual and thereby also environmental work in the company.

Furthermore, decision making models applied on the management of manufacturing operations often include implicit assumptions that people are predictable, emotionless, observable, and deterministic in their decision-making and actions, and independent of others (Bendoly et al. 2006, p.740). This is limiting our understanding of how environmental concerns can be integrated with the day-to-day technical work in manufacturing operations. Therefore, the present model is based on the viewpoint that reality and decision making is socially constructed, using March and Olsen's rule-based actions and decision making (March & Olsen 1989).

Similarly, LCA research has been hampered by a focus on innovating new LCA tools, even though practice research show that a lack of tools is not a problem (Baumann 2009). I believe further research in LCA and the application of LCA merit the perspectives on decision making that has been presented here. The steps taken to include actors, and their power of influence, in the life-cycle models of physical flows of matter, are important, but still the field of research is underexplored. The practical need of focusing on the application and actors using the results from LCAs is expressed e.g. through the European Commission's focus on application situations in their recent LCA manual (JRC European Commission 2010).

7.4 Managerial implications

Engaging in environmental life-cycle management currently means to do more than what is legally required. Previous literature has nevertheless demonstrated several business benefits of going beyond legal compliance. Examples include improved financial performance (Porter & Kramer 2006), and improved reputation (Potoski & Prakash 2005b). However, what makes business sense from the perspective of top-management in a large company may not be as obvious for middle or lower level management. This thesis has presented arguments for why engineering roles are important, ways assessment methods can be applied to gain an understanding of manufacturing environmental impacts, as well as, models explaining action or inaction in the organization. In a bullet list below I outline, based on the findings of this thesis, some of the issues that may be of interest for an operations manager engaging in life-cycle management in manufacturing.

- The direct and indirect environmental concerns are of a different character, and need to be treated in different ways in the organization. The upcoming energy management standard ISO 50001 (ISO Central Secretariat 2011) is intended to provide external pressure, similar to the ISO 14001 management standard, however two things need to be said. First, for many manufacturing firms, reducing energy intensity is not associated with a legal pressure to the same extent as reducing direct emissions. Second, if the auditing system in environmental management system is providing an external part with sufficient power to influence the organization, part of the life-cycle challenge would nevertheless remain. The self-regulatory mechanisms of the ISO 50001 systems would not apply to the indirect environmental impacts stemming from material waste/inefficiency in the organization's manufacturing processes.
- The stakeholder perspective and the drivers for environmental life-cycle management are different for the company as a whole, than for individuals working in the company, engineers or factory managers.

- Rather than putting faith in value-driven environmental champions, the present studies support the idea that environmental issues should be included in the day-to-day technical improvement work in manufacturing. The decision making model includes five factors that are influencing whether green practices will appear. Only one of these includes personal values as driver of initiatives. It is suggested to assess how benign the situation is for the engineers in the organization to include environmental aspects, using the five perspectives given in the model presented in section 5.2.
- When tools and processes are adapted to include environmental aspects, the environmental performance of *manufacturing processes* and the environmental performance of the *product* should be considered separately, as complementary views.

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APPENDIX: SUMMARY OF APPENDED PAPERS

The papers appended to this thesis contribute to the understanding of how environmental aspects can become integrated into the standard tasks of manufacturing engineers. Knowledge is generated on two perspectives. On the one hand, we *develop methods for the quantification* of life-cycle environmental impacts; on the other hand, we *explore the work practice* of the engineers in manufacturing. The work practice papers are widening the analysis to view the whole socio-technical context of manufacturing engineering work. This is a reality heavily dependent on numbers but where calculation tools are only one of several components influencing actions.

The proposed quantification methods target the need to produce results that make sense for people working in manufacturing. Modeling is done considering (1) that the engineers' domain of influence is limited and not encompassing the whole value chain (Paper I), and (2) their large possibilities to modify, in detail, the part of the product life cycle they work in (Paper II). Paper III is an overview of LCA methods considering actors' ability to influence energy and materials flows in a system.

Based on a field study a model is proposed for understanding what constitutes preferable conditions for engineers to make decisions and take actions improving the environmental performance (Paper VI). The thinking presented in Paper I on the management of environment in manufacturing is applied for understanding how the life-cycle perspective in manufacturing is challenging contemporary management practices and research (Paper V).

PAPER I: MANUFACTURING ACTOR'S LCA.

Life-cycle assessment (LCA) has been an important tool in industry to understand systemic environmental effects of technological choices and behavior. In the procedure, a life-cycle model of the product is constructed, and the inputs and outputs of 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.

This paper argue, with support from earlier empirical findings (Heiskanen 2000), that while the results of an LCA can be an eye-opener, the holistic perspective risk of blurring results be a barrier to pro-environmental actions. No single individual or industrial actor can influence the whole life cycle of a product, captured in the results of a mainstream LCA. To be effective, analysis methods intended to support improvement actions should therefore also consider the decision makers' power to influence (Baumann et al. 2011). The results of the analysis should speak directly to the intended audience and relate to what they consider in daily work.

For this purpose this paper presents an approach with which manufacturing decision makers can sharpen the focus in LCA from a conventional 'products or services' emphasis to a company's manufacturing processes. The method has been developed via a continuous conceptual refinement process using existing literature and a new empirical findings from an LCA study of a manufacturing line, including data collection, model building, and model evaluation.

A key feature of the suggested approach is to calculate the environmental consequences of energy and material losses in manufacturing rather than merely accounting for the contributions of individual stages of the life cycle to the overall environmental impact. The processes of transforming and assembling material are the focus rather than the product itself. The paper demonstrates how fundamental methodological choices in an LCA are changed by using this perspective. The utility to which the environmental distress is related in an LCA (functional unit) becomes 'the manufacturing of the product at company X' instead of as conventionally 'the function provided by the product in use'. The system included in the analysis (system boundaries) is limited by what is assumed to be controlled by engineers in manufacturing. In doing so, the environmental impacts from processes after manufacturing are omitted in the analysis. In addition, *part of* the environmental impacts related to producing the product is disregarded, namely, the production of the materials contained in the finished product. It is assumed that the decision spaces of most decision makers dealing with the environmental performance of manufacturing systems concern energy use and material losses rather than product design.

The method identifies and directly relates the environmental consequences of emissions or raw material inputs in the product life cycle to manufacturing processes. In doing so, the holistic systems perspective in LCA is somewhat diminished in favor of the relevance of results to manufacturing decision makers.

The paper concludes by highlighting benefits and limitations by discussing the proposals in relation to more conventional LCA modeling with a product focus, by identifying problems using the decision domain to define system boundaries, and the difficult task of assessing improvement potentials.

Author contributions: B.L. and A-M.T. designed research; B.L. and B.R. collected data; B.L. and B.R. did the numerical modeling; B.L. and B.R. analyzed data; and B.L. and A-M.T. wrote the paper.

PAPER II: RELATING MANUFACTURING SYSTEM CONFIGURATION TO LIFE-CYCLE ENVIRONMENTAL PERFORMANCE: DISCRETE-EVENT SIMULATION SUPPLEMENTED WITH LCA

This paper proposes a method for combining discrete-event simulation (DES) – commonly used for the conceptual evaluation of manufacturing systems – with life-cycle assessment (LCA). This combination captures the dynamic interrelationships between manufacturing processes in order to analyze systemic responses to configuration changes, something static LCA modeling cannot do.

The method evolved when a bearing production line was being examined to relate manufacturing decision making to environmental consequences, as defined in Paper I. This was done using DES to investigate how parameters normally used to optimize traditional manufacturing system performance influence energy use and material losses in manufacturing systems. The environmental consequences of this material loss and energy use are further calculated using LCA methodology. The method uses more detail for the processes a company can fully control than for other processes in the life cycle. DES is used to quantify the material and energy inputs and outputs of these parts of the system, and multiply those by LCA factors representing the upstream or downstream environmental consequences of these inputs or outputs.

While the method inherits several characteristics from previous work in the area, it also introduces new considerations into the environmental modeling of manufacturing. The paper applies the manufacturing decision-maker’s perspective, as presented in Paper I. This framework in combination with DES enables us to pinpoint the most dominant aspects, contributing to environmental impact, in the work of a specific function in manufacturing. The method also suggests how to model electricity indirectly used by production machines, for example, via compressed air or hydraulic oil.

Results indicate that while the combination of the two methods increases the data collection workload, it uncovers previously hidden environmental consequences of manufacturing decision making and introduces a way to asses an industrial actor's manufacturing system using relevant LCA scenarios.

Author contributions: B.L. and A-M.T. designed research; B.L. collected data; B.L. did the numerical modeling; B.L. analyzed data; and B.L. and A-M.T. wrote the paper.

PAPER III: THE USEFULNESS OF AN ACTOR'S PERSPECTIVE IN LCA

This paper put the manufacturing actor's LCA method in Paper I in a relation the other LCA modeling approaches using an actor's perspective. It is essentially an argumentation for adding an actor's perspective to life- cycle assessment (LCA). The need for this perspective stems from a criticism about the usefulness of LCA interpretation methods comparing the relative contribution of life-cycle phases of a product. Our argumentation is based on four previously published studies providing practical examples of how value chain actors' influence may be considered in an LCA and the benefit of doing so. Manufacturing sector examples show how one company's influence can be illustrated in results and how it may relate all relevant emissions to its own processes. The food sector study shows how to assess several value chain actors' individual improvement potential. The final example, taken from building sector, explore how to consider the fact that actors in one part of the value chain can influence other actors to improve.

Author contributions: B.L. designed research; and all authors wrote the paper.

PAPER IV: IN SEARCH OF APPROPRIATE CONDITIONS FOR 'GREEN' PRODUCTION ENGINEERING: LESSONS FROM THE FIELD.

Much of what is written about barriers, drivers and determinants on corporate green behavior implicitly aims at answering questions such as "Why do organizations act in certain ways?" and "What can policy makers do to stimulate the greening of organizations?". This paper is shifting the research focus to a lower organizational level that is closer to the technical core of the organization. For a manager who is asking "What can I do to stimulate green actions in my organization?" the key is to understand why individuals in different work roles take green actions or refrain from taking such action. The paper, built in a collaborative research project with a company with ambitions in this direction, presents a model of the factors that influence whether production engineers will include environmental performance of the production process in their everyday work practice. The model suggests that the situational interplay between five factors—competence, direct stakeholders, resources, organizational infrastructure, and the technical system—determine the environmental outcome of the engineering work. The five-factor model is developed by viewing the empirical findings through a 'logic of appropriateness' lens.

Author contributions: B.L. designed research; B.L. and G.K. collected data; B.L. and G.K. analyzed data; and B.L. and G.K. wrote the paper.

PAPER V: THE PRACTICE OF ENVIRONMENTAL LIFE-CYCLE MANAGEMENT IN MANUFACTURING: ROLES AND RESPONSIBILITIES

This paper explores the practical organizational challenges for a company in the transition from facility-oriented to life-cycle environmental management in manufacturing. We use the case from a manufacturing site of a multinational corporation six years after the company's launch of a new integrated business and environmental strategy that included strong elements of environmental life-cycle consideration. We distuingish between organization practices related to *direct* environmental concerns from those that are *indirect,* using an LCA framework for understanding the physical system of energy and material flows. We show how the work to reduce indirect environmental impacts of manufacturing operations are in larger need, than direct emissions, of being driven by manufacturing and engineering managers, and thus be included in the normal work of improving the technical performance of the manufacturing process. The case also indicates that life-cycle environmental concerns risk being deminished in a management system where environmental and occupational health and safety issues are co-managed.

Author contributions: B.L. and A-M.T. designed research; B.L. and G.K. collected data; B.L., G.K. and A-M.T. analyzed data; and B.L. and G.K. wrote the paper.