Integration of Design for Environment in the vehicle manufacturing industry in Sweden

*Focus on practices and tools*

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Licentiate thesis in Planning and Decision Analysis with specialization on Environmental Strategic Analysis

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Abstract

Design for Environment (DfE) promotes the systematic consideration of environmental aspects during product design and development. Despite the maturity of concepts and tools in literature, efficient implementation in industries is reported to be low. A need to bridge this gap is identified with studies that look on DfE practices as well as the use and potential of DfE tools.

This thesis is part of a research project that investigates DfE practices and the use of tools during vehicle design and development. The aim is to investigate the ways that environmental constraints can be efficiently integrated into product development processes thus assist in improving the environmental performance of products from a life cycle perspective. The scope of the study includes four vehicle manufacturing companies in Sweden. The development and utilization of tools has been also investigated aiming to increase the opportunities for effective use within this product category. Case study methodology, research interviews and literature reviews constitute the research strategy followed in this work.

The empirical results presented in this thesis indicated that vehicle manufacturing companies in Sweden are continually working to improve the environmental performance of their products and meet legal and customer demands. Despite similarities regarding the type of environmental requirements considered, the companies studied have adopted different ways to identify and integrate environmental requirements into their product development process and use DfE tools to different extents. Such variations reflect differences in the success and maturity levels of the DfE practices adopted.

A need for increased and more systematic use of tools is identified for all studied companies and especially for analytical tools. Results from the literature review showed that a variety of tools are available that have the potential to support vehicle design processes. However, only a few cover a broad set of aspects identified to be relevant from a vehicle design perspective. For DfE tools to become effective and be used during product development, they need to cover aspects that are relevant for the company and product designers. A need towards the development of tools that assist vehicle or product designers in general, to make informed and comprehensive choices based on a variety of requirements associated to the product, is identified.

Keywords: Design for Environment (DfE), ecodesign, vehicle design, DfE tools, ecodesign tools, product development, integrated product development
Preface

This thesis provides a summary of the first part of my studies as a PhD student, in the PhD program of “Planning and decision analysis – with focus on Environmental strategic analysis”, offered by the Division of Environmental Strategies Research (fms) at KTH. It is conducted as part of the research project “Coupling Materials-Environmental Analysis” and more specifically the Environmental Effects subproject, at the Vinnova Excellence Center for ECO² Vehicle Design. The center is a cooperation between academic departments at KTH, vehicle related manufacturing industries and transport authorities in Sweden. The center provides a node for multidisciplinary research on different aspects related to vehicle design and transport solutions incorporating research both on road and rail vehicles.

List of papers included in the thesis


Submitted to Journal of Cleaner Production

**Paper II**: Sofia Poulikidou, Anna Björklund. Overview of Design for Environment tools and investigation of their application potential within vehicle design and development processes.

Submitted to Journal of Engineering Design

Contribution of the author

The author was responsible for planning, data collection, analysis of results, and writing of the main parts of Papers I and II. Papers I and II were initially scoped and then revised with the author’s supervisors, Assoc. Prof. Anna Björklund and PhD Sara Tyskeng.
Acknowledgments

I am sincerely thankful to all the people who, in different ways, contributed to this work. I wish to thank especially:

The Centre for ECO² Vehicle Design for funding this project and providing me the means to perform this work.

All employees at the four companies who participated to the interview study, for their cooperation and time.

Assoc. Prof. Anna Björklund, my main supervisor, for her valuable guidance and continuous encouragement during my studies. I would also like to thank my co-supervisors Assoc. Prof. Per Wennhage for always being enthusiastic and supportive, and Dr. Sara Tyskeng for believing in me and inviting me to the “world of research”.

Dr. Anna Hedlund Åström and Prof. Ulf Olofsson for their constructive feedback on my cover essay.

Dr. Åsa Svenfelt for her valuable help at the beginning of my studies.

All my colleagues and friends at “fms” for providing an inspiring and friendly working environment. Special thanks to Sofia, Yevgeniya, Jacob and Mohammad for all beautiful moments inside and outside fms, as well as to my kind roommates Luciane, Ulrika and Greger.

My colleagues at the Centre for ECO² Vehicle Design and other departments at KTH for sharing our research ideas and interests.

All my friends here in Sweden, in Greece but also in other parts of the world for all memorable moments.

My beloved family for their encouragement, love and for always being by my side.

My dear parents Anastasia and Giorgios, and my sister Despoina for their endless love, care and support. Ένα πολύ μεγάλο ευχαριστώ για την φροντίδα και την αγάπη σας!!

Last but definitely not least, I would like to thank Dimitris. Thank you for inspiring me with your passion for research and for being so supportive, patient, encouraging, helpful…I could probably continue for ever...

Sofia Poulikidou
Stockholm, 20th of November 2013
List of abbreviations

CE Concurrent Engineering
CED Cumulative Energy Demand
CO₂ Carbon dioxide
DfE Design for Environment
DfR Design for Recycling
E2PA Environmental efficiency potential
EC European Commission
ECO² Ecology Economy
EDST Environmental Design Support Tool
EEA Environmental Effect Analysis
EFMEA Environmental Failure Mode Analysis
E-LCC Environmental Life Cycle Cost Analysis
ELV End of Life Vehicle
EPS Environmental Priority Strategies
EQFD Environmental Quality Function Deployment
ERA Environmental Risk Assessment
ERPA Environmentally Responsible Product Assessment
GADSL Global Automotive Declarable Substance List
HoE House of Ecology
IMDS International Material Database System
IPD Integrated Product Development
ISO International Organization for Standardization
LCA/E-LCA Life Cycle Assessment / Environmental Life Cycle Assessment
LCDSM Life Cycle Design Structure Matrix
LCE Life Cycle Engineering
LCM Life Cycle Management
LC-QFD Life Cycle Quality Function Deployment
LCT Life Cycle Thinking
MCA Multi Criteria Analysis
MECO Materials, Energy, Chemicals and Other
MET Materials, Energy, Toxicity
MIPS Material Intensity per Unit Service
NOx Nitrogen oxide
OPM Oil Point Method
PM Particulate matter
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1 Introduction

1.1 Products and the environment

There is no doubt that the majority of ecological challenges that societies need to address today (resource depletion, climate change, biodiversity losses and more) result from the constantly increasing number of goods that these societies produce, use and dispose.

Products generate positive and negative impacts on the environment that may occur at different stages during their life cycle i.e. from resource extraction, to production, use phase and final disposal. It can be claimed however, that the life cycle of a product begins already during the design and development stages. Decisions taken during those stages will determine not only functions and properties of the product but also its environmental performance. Various authors claim that more than 80% of the environmental impacts are introduced during those stages (Bhamra, 2004); for instance through the selection of materials and manufacturing processes, the energy demands for the production and operation of the product or the end of life treatment possibilities. It can therefore be admitted that product design and development are critical stages for the “environmental adaptation” of products (Ritzén, 2000) as well as for the transition of our society towards sustainable development.

Based on these principles the concepts of Design for Environment (DfE) and ecodesign have emerged that promote the systematic consideration of the life cycle environmental performance of a product during the design and development stages. Academia offers a rich field of research around DfE and how environmental aspects can be efficiently integrated into product design stages along with a variety of methods and tools that have been developed to enable such integration.

Despite significant benefits and the rich literature records on this approach, there are challenges regarding the ways that it can be adopted in practice (Bey et al., 2013; Boks, 2006). Researchers in the area of DfE have identified and demonstrated a gap between methodological development and the diffusion level of the DfE approach and tools in industries (Handfield et al., 2001; Tukker et al., 2000). In recent studies (Bey et al., 2013; Deutz et al., 2013; Jönbrink et al., 2013; Short et al., 2012) the implementation gap remains evident. To this end, a need to bridge this gap has been identified through empirical studies that can explore the integration of DfE in various product categories and industrial sectors. Empirical studies may “prove to be instrumental in furthering the implementation of sustainable product innovation practices, and as such, constitute to the transition of this field” as pointed out by Boks and McAloone (2009).

1.2 The vehicle design paradigm

The demand for transportation of people and goods is expected to increase during the forthcoming years. Being a major consumer of resources and energy, the transport sector today gives rise to significant challenges for the sustainable development of societies and therefore receives global attention. The transport sector (including road, railroad, sea and air transports),
accounts for about a third of the total energy demands in Europe, while similar trends are observed for the total emissions of carbon dioxide (CO₂) and other pollutants (European Commission, 2012). Among these, more that 80% is accounted to road and rail transports and specifically to the operation of road and rail vehicles (European Commission, 2012).

A number of legislation measures have been initiated at European and global level that aim to minimize and control the environmental impact of transports especially when it comes to road transports. The European Commission (EC) for instance, has set emission targets for road vehicles on a variety of pollutants, among other carbon dioxide (CO₂), particulate matter (PM) and nitrogen oxides (NOx) (European Commission, 2009; European Parliament, 2012) that are connected to major environmental impacts such as climate change, air pollution, ozone depletion etc. Moreover, as an attempt to minimize the amount of waste produced and the losses in valuable resources, a directive for End of Life Vehicles (ELV) (European Parliament, 2000) has been introduced. According to this directive, from 2015, 85% of the weight of the vehicle should be recycled or reused.

Multiple measures and innovations have been introduced by the vehicle manufacturing industry in order to address their environmental challenges and comply with the existing and constantly increasing regulation. Examples include the development of electric engines, alternative fuels and more efficient combustion engines, as well as the trends towards light weighting of vehicles. Despite the remarkable efforts however, recent studies show that the environmental impact of the sector remains significantly high while new challenges are emerging.

The development and use of lightweight materials for instance (i.e. plastics and various types of composites) has a negative effect on the recyclability rates of vehicles as well as on the increased energy demands for their production (Van Acker et al., 2009; Witik et al., 2011). Another example comes from the electrification of the sector. Although electric vehicles have the potential to reduce the emissions’ level during the use stage significantly, the negative environmental consequences have been shifted to other stages of the life cycle i.e. product manufacturing as well as end of life (Hawkins et al., 2013).

These examples illustrate that a significant number of trade-offs arise based on the current paradigm of vehicle design which need to be considered when future products are developed. Vehicle manufacturers as well as product developers in general should have (but maybe most important make use of) the means to identify and estimate those trade-offs in order for efficient improvements to be applied.

**1.3 Background to the research project**

This thesis is part of a research project conducted at the centre for ECO² Vehicle Design at KTH, Royal Institute of Technology in Sweden. The centre is a collaboration between academia, the vehicle manufacturing industry and transport authorities in Sweden, with the aim to provide vehicle design solutions that contribute to sustainable development of the transport sector. “ECO²” stands for Ecology and Economy. For this reason, research within the centre seeks to incorporate functional aspects of vehicle design with environmental and economic constraints.
In this specific research project the ways that environmental aspects are included into vehicle design processes are investigated. The ultimate objective of the project is to investigate and identify ways for vehicle designers to consider functional, economic and environmental aspects in a systematic and consistent way during product development and particularly during material selection processes. In the work presented in this thesis, an initial step towards the development of such an approach is performed by acknowledging the importance of understanding first the processes and tools that are already in place for the companies studied.

For this reason, this thesis provides an interplay between theory and practice around the ways that environmental aspects can be integrated into product development processes and design decisions. Special attention has been given to the use and adoption of DfE tools as a way to identify strategies and solutions that would improve the life cycle environmental performance of vehicles.

1.4 Aim and scope of the thesis

The overall aim of this thesis is to investigate the ways that environmental constraints can be efficiently integrated into product development processes in order to assist in improving the environmental performance of products from a life cycle perspective. In particular, the development and utilization of tools has been investigated aiming to increase understanding on the opportunities, barriers and needs for their successful and increased use. This thesis is specifically looking to the vehicle manufacturing industries and the integration of environmental aspects and the use of DfE tools during vehicle design. The scope of the study includes four vehicle manufacturing companies in Sweden that produce road and rail vehicles.

To fulfil the aim of this thesis, the research questions that need to be answered include:

**Q1:** Which environmental aspects and requirements are prioritized today by the vehicle manufacturing industry in Sweden and how are those aspects integrated into product development processes?

**Q2:** What types of supporting tools are utilized by the vehicle manufacturing industry in Sweden? What limitations and needs can be identified with regard to the current use of tools within the studied companies?

**Q3:** Do existing tools contain features that have been identified as important to be able to support vehicle design? What aspects are covered and what is missing from a vehicle design perspective?

1.4.1 Delimitations

This thesis investigates the ways that four vehicle manufacturing companies in Sweden incorporate environmental aspects into their product development process. Therefore, the results should be treated accordingly and should not be generalized for all organizations within this sector.
It should also be noted that the focus of this research concerns the physical product and the environmental attributes and considerations connected to that. Environmental management systems that the companies involved in this study might have adopted, as well as aspects that concern the in-house environmental performance of these organizations are not considered in this thesis. The focus of this work is on the vehicle development process and aspects that affect the physical end products manufactured by the companies.

1.4.2 Summary and contribution of the appended papers

This section provides a short summary of the two appended papers and illustrates the ways that they contribute to the research questions of this thesis.

- Paper I: “Empirical study on integration of environmental aspects into product development: processes, requirements and the use of tools in vehicle manufacturing companies in Sweden”

Paper I investigates the implementation and diffusion of the DfE approach in four different vehicle manufacturing companies in Sweden by exploring the practices and procedures followed by those companies. The results of Paper I provide insights on the product development process followed during vehicle design, the environmental aspects prioritised, the people involved as well as the DfE tools that are mainly used in these specific companies. Although it was not a normative study of what companies “should” do, comparisons with success factors obtained from the literature were used to discuss the findings of the study and highlight best practices, as well as areas for further improvement.

- Paper II: “Overview of Design for Environment tools and investigation of their application potential within vehicle design and development processes”

Paper II provides an overview of 31 tools for supporting and facilitating the integration of environmental aspects into product design and development processes. It analyses the tools based on a selection of criteria that cover methodological aspects of the tools and further evaluates their potential to be used within the vehicle design process. The aforementioned criteria were obtained from the literature as well as empirical data from vehicle manufacturing companies. The results of Paper II provide knowledge on the DfE tools that are available today. Moreover it identifies aspects that would assist in developing tools that are relevant for vehicle design as well as product design in general.

The research questions covered by each of the papers are illustrated in Table 1.

<table>
<thead>
<tr>
<th>Papers included in the thesis</th>
<th>RQ 1: Integration of environmental aspects</th>
<th>RQ 2: Integration of tools</th>
<th>RQ 3: The applicability of DfE tools during vehicle design</th>
</tr>
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<tr>
<td>Paper I</td>
<td>X</td>
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<tr>
<td>Paper II</td>
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<td>X</td>
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</table>
1.5 Outline of the thesis

This thesis consists of a cover essay and two appended papers. The first chapter of the cover essay has presented a short background as well as the aim and scope of this work. The remaining sections are organized as follows: Chapter 2 provides the theoretical context of the thesis while Chapter 3 describes the methodology followed. The findings of the two papers are summarised and discussed in Chapter 4 which concludes with a reflection on the methodology of this thesis. The main conclusions and contribution of this thesis are presented in Chapter 5. The final chapter of the cover essay (Chapter 6) presents ideas for further research and continuation of this work.
2 Theoretical context

This chapter provides an overview of the concepts and theories used and discussed throughout this thesis. It expands the background given in Papers I and II and serves as the theoretical foundation of those papers. More specifically, sections on product design and development, DfE and success factors refer to Paper I and the first research question of this thesis. The section on DfE tools provides the background for both papers. It assists the discussion of the findings of Paper I and thus research question 2 and serves as the foundation for Paper II and research question 3 of this thesis. The section on requirements and selection of DfE tools assisted mostly in scoping and discussing Paper II.

2.1 Product design and development

Product development can be defined as the process that transforms a market opportunity into technical and commercial solutions (Whitney, 1990). It consists of various activities and steps that need to be followed in order to transfer an idea or market need, into a finished product. Different models exist in literature describing the activities involved during the product development process. An indicative model developed by Ulrich and Eppinger (2008) is shown in Figure 1.

![Figure 1 A generic model of the product design and development process and stages involved according to Ulrich and Eppinger (2008)](image)

Product development was traditionally carried out as a stepwise and linear process where one activity started when the previous was finished; a process known as serial engineering. Nowadays, product development is a more integrated and systematic activity with many iterative and interconnected steps. This new way of working can be found under the terms: integrated product development (IPD), concurrent engineering (CE) or life cycle engineering (LCE) (Hallstedt, 2008; Tingström, 2007). Key characteristics of this integrated approach are (Lindahl, 2005):

- optimized and integrated work procedures,
- exchanges of information and knowledge, as well as the
- use of supporting tools.

Product development activities are usually organised in parallel projects where multidisciplinary teams are involved (Hallstedt, 2008; Lindahl, 2005; Tingström, 2007). An illustration of this process is shown in Figure 2. Additional models on IPD and design methodologies are included in the review study performed by Tomiyama et al. (2009).
Among the encountered advantages of IPD in relation to serial models are the possibilities for communication between the various phases and teams, time efficient processes, lower risks for delays and additional costs, increased creativity, better communication with suppliers and customers of the organization (Hallstedt, 2008).

Within the different models for serial or integrated product development processes a number of common activities can be identified that can be considered as the stages where key decisions regarding the product are taken (Deutz et al., 2013; Schlüter, 2001):

- product planning (problem identification and analysis, outline of the task)
- conceptual design (generation of concepts, ideas and design solutions)
- detailed design (selection of the most feasible solution and design specifications, determining the precise product).

During all those stages a multitude of requirements and constraints need to be fulfilled that are related to functional and non-functional properties of the product such as dimensions, materials, life span, ergonomics, quality, performance, aesthetics, safety and cost (Luttropp & Lagerstedt, 2006). In the context of product development requirements can be defined “as a description of a set of testable conditions applicable to products or processes. Requirements should be satisfied by a product if a test or observation reveals that the described conditions are met” (Fiksel, 2011). Product designers have the task to ensure the compliance of the product with various design requirements, standards and regulations but also meet market and customer demands. As products become more complex the different requirements and parameters to be fulfilled increase accordingly.

2.1.1 The early stages of product development

Bhamra (2004), points out that “early stages” of product development should refer to the pre-specification stage, the product planning stage and concept and strategic design i.e. activities that take place before the product detailed design specification phase. During those early stages the degree of design freedom is higher allowing product developers and design engineers for major and more innovative improvements. The closer we move in time towards the complete product, fewer opportunities for modifications exist. A “design paradox” then occurs since the knowledge about the product follow the opposite trend (Ullman, 2002) as cited in (Lindahl, 2005). By the
time sufficient information is obtained, modifications might be no longer possible or feasible for various reasons including functional or economic ones (Lindahl, 2005; Luttropp & Lagerstedt, 2006).

2.2 Design for Environment (DfE)

Design for environment (DfE) is an approach that promotes the early and systematic consideration of environmental aspects and requirements during product development in order to minimize the negative impacts of products on the environment. It emerged during early 1990’s and is defined as “a process, integrated within the design and development that aims to reduce environmental impacts and continually improve the environmental performance of the products, throughout their life cycle from raw material extraction to end of life” (ISO TR/14062, 2002).

As environmental aspects all “elements of an organizations activities, products or services that can interact with the environment” are considered (ISO TR/14062, 2002). Environmental aspects can be direct, resulting from activities that the organization can influence and control, or indirect, from activities that the organization can be expected to have an influence on, but no control of.

DfE can be found under various terms namely: ecodesign, green design, environmental conscious design, life cycle design, design for eco-efficiency, sustainable product design (Bhamra, 2004; Fiksel, 2011). In this thesis the terms DfE and ecodesign are used. Although some authors identify differences between these two terms, in this thesis they are considered synonymous and therefore used interchangeably.

The rich literature around DfE, concludes to a number of key principles of the DfE framework. These principles can be summarised as follows:

- (Early) consideration of environmental aspects into product development
- Life cycle thinking
- The use and integration of supporting DfE tools

2.3 Consideration of environmental aspects into product development

As the demand for environmentally friendly products increase, environmental aspects need to be considered during the product design stages together with all other requirements such as cost, performance, safety, quality etc. (ISO TR/14062, 2002; Luttropp & Lagerstedt, 2006). Incorporating the environmental performance of the product during the early phases of product development is the most efficient way to minimize the adverse effects of products on the environment (Bhamra, 2004). The motivation behind this idea is twofold. Not only are most of environmental aspects determined during design decision, but as presented in section 2.1.1 the design freedom during those early stages is higher. As a result, many organizations have encountered economic benefits when environmental considerations are introduced in the design process (Plouffe et al., 2011).
A generic model for ecodesign is presented in the technical report of the International Organization of Standardization (ISO) that suggests different actions and activities that may facilitate the integration of environmental aspects during product development. The model is shown in Figure 3:

![Diagram of a generic model for integrating environmental aspects into product development. Figure redrawn from ISO TR/14062 (2002)](image)

2.4 Life cycle thinking

The DfE approach encourages designers and all actors involved in the product design process, to think outside the technology, functional and economic performance of the product and incorporate a broader perspective that includes all stages of its value chain (Fiksel, 2011). The term “life cycle” can be then defined as: “the successive and interconnected stages of a product system, from the extraction of raw materials or natural resources, to the manufacturing, use, recycling and final disposal” (ISO TR/14062, 2002).

Life cycle thinking provides a holistic picture of the product and the system in which it is embedded. A major advantage of the life cycle thinking approach is the possibilities offered for the identification and minimization of trade-off situations when the environmental impacts of one activity or life cycle stage are transferred to other activities or life cycle stages of the product.

Life cycling thinking provides the foundation for a variety of frameworks or methodologies (in addition to DfE); for instance, Life Cycle Assessment (LCA) and Life Cycle Management (LCM).
LCA is a methodology that can be used in order to identify and quantify the environmental impact that results from activities that take place during the life cycle of a product or service. Guidelines for conducting LCA studies are available (EC-JRC, 2010; ISO 14040, 2006). LCM is based on the same principles but it can be considered as a more business oriented approach that integrates the life cycle performance of a product or service with the value chain and economic activities of the organization (UNEP/SETAC, 2009).

### 2.5 DfE tools

The use of tools is frequently mentioned in literature as an essential part of the DfE approach (Johansson 2002; Le Pochat et al., 2007; Lindahl, 2005; Ritzén, 2000; Tingström, 2007) and as a way to provide methodological support during the integration of environmental aspects into product development (Hallstedt, 2008). The term “tool” in this context is defined in a broad sense as any type of systematised aid to incorporate environmental aspects into the product design and development process.

A significant number of tools are available today and can be used for various purposes: to assess and monitor the environmental performance of a product as well as to suggest, generate or compare improvement strategies (Baumann et al., 2002; Brezet & Hemel, 1997; Byggeth & Hochschorner, 2006; Fiksel, 2011; Hallstedt, 2008). The overall goal of such tools is to provide design engineers and product developers with information on the environmental performance of the product and guide them to the most relevant improvement strategies.

DfE tools may vary in complexity, data and expertise requirements i.e. from generic manuals and guidelines to more sophisticated analytical tools (Baumann et al., 2002). They can be qualitative or quantitative and can be presented in a variety of forms and structures; like radar graphs, matrices, checklists or computer based tools (Poulikidou, 2012).

DfE tools in Paper II are classified into three categories: prescriptive, analytical and tools that identify strategies.

- **Prescriptive tools**

  Prescriptive tools can be found in the form of checklists, list of strategies or guidelines. Such tools are created with the purpose to guide and provide recommendations to design engineers on aspects that influence the environmental performance of a product and that should be considered during the early product design stages. They can be also used to monitor and control the environmental performance of products under a specific aspect or requirement.

- **Analytical tools**

  This is a broad category of tools that provide a detailed or more simplified assessment of the environmental performance of the product based on the products properties and characteristics. Analytical tools can be used to assess the environmental impact of the product, identify hotspots as well as to compare different product design alternatives. Analytical tools can be found in the form of matrices, graphs or indicators as well as in the form of computer based tools.
Tools that identify design strategies

A variety of tools can be found with the purpose of identifying design strategies, which may lead to improvements of the environmental performance of the product. Such tools support and guide designers to the identification of improvement strategies based on various criteria among others cost, customer requirements etc.

In addition, procedural tools are available in this context as well (Byggeth et al., 2007; Howarth & Hadfield, 2006; Simon et al., 2000). Although not addressed in detail in this thesis, procedural tools aim to support companies on the procedures which need to be followed in order to assist the integration of environmental aspects into product development (Wrisberg et al., 2002).

A compilation of 31 tools, that are available today for integrating environmental aspects into product design, is provided in Paper II. The list of DfE tools accompanied with a short description is displayed in Table 2. For additional information and more detailed analysis of the tools see Paper II.
Table 2 List and short presentation of a sample of tools for integrating environmental aspects into product design, as identified in Paper II

<table>
<thead>
<tr>
<th>Name of the tool</th>
<th>Short description</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Prescriptive tools</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Ecodesign checklist</td>
<td>A list of aspects and design strategies that product designers should consider during product design processes</td>
<td>(Brezet &amp; Hemel, 1997)</td>
</tr>
<tr>
<td>Ten golden rules</td>
<td>Ten generic guidelines for ecodesign</td>
<td>(Luttropp &amp; Lagerstedt, 2006)</td>
</tr>
<tr>
<td>Material and Chemical Control Lists</td>
<td>List of threshold values on restricted and prohibited substances.</td>
<td>(e.g. Global Automotive Declarable Substance List (GADSL),(American Chemistry Council Inc., 2013))</td>
</tr>
<tr>
<td><strong>Analytical tools</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Simplified assessment</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Eco Design Strategy Wheel</td>
<td>Assessment of the performance of the product under eight criteria. The tool can be used to compare different product alternatives.</td>
<td>(Brezet &amp; Hemel, 1997)</td>
</tr>
<tr>
<td>E-concept Spiderweb</td>
<td>Assessment of the performance of the product under eight criteria. The tool can be used to compare different product alternatives.</td>
<td>(Tischner, 2000)</td>
</tr>
<tr>
<td>ABC analysis</td>
<td>Assessment of the performance of the product under eleven criteria.</td>
<td>(Byggeth &amp; Hochschorner, 2006)</td>
</tr>
<tr>
<td>Materials, energy, chemicals and other matrix (MECO)</td>
<td>Assessment of the performance of the product under four impact categories: materials, energy, chemicals, and other (any aspect that cannot be included in the previous ones).</td>
<td>(Byggeth &amp; Hochschorner, 2006)</td>
</tr>
<tr>
<td>Materials, energy and toxic emissions matrix (MET)</td>
<td>Assessment of the environmental performance of the product under three impact categories: materials, energy and toxicity.</td>
<td>(Brezet &amp; Hemel, 1997)</td>
</tr>
<tr>
<td>Environmentally Responsible Product Assessment (ERPA) or Streamlined LCA</td>
<td>Assessment of the environmental performance of the product under five impact categories: materials, energy use, solid residues, liquid residues and gaseous residues.</td>
<td>(Graedel, 1998)</td>
</tr>
<tr>
<td>Advanced assessment</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Environmental Life Cycle Assessment (E-LCA)</td>
<td>Tool that evaluates the environmental impact of a product or service during its life cycle. Can be used to identify hotspots as well as to compare product or design alternatives.</td>
<td>(ISO 14040, 2006)</td>
</tr>
<tr>
<td>LCA Software tools</td>
<td>Computer based tools that facilitate the implementation of the LCA methodology.</td>
<td>(e.g. SimaPro, GaBi, TEAM™ Ecobilan Life Cycle Assessment, openLCA)</td>
</tr>
<tr>
<td>Environmental Life Cycle Cost Analysis (E-LCC)</td>
<td>Tool that evaluates the environmental cost and externalities of a product during its life cycle.</td>
<td>(Ciroth et al., 2008; Wrisberg et al., 2002)</td>
</tr>
<tr>
<td>Name of the tool</td>
<td>Short description</td>
<td>Reference</td>
</tr>
<tr>
<td>------------------</td>
<td>-------------------</td>
<td>-----------</td>
</tr>
<tr>
<td>Life Cycle Design Structure Matrix (LCDSM)</td>
<td>This tool provides the user with an overview of the environmental performance the product during its life cycle and assists to identify flows and interactions among the different components and activities.</td>
<td>(Schlüter, 2001)</td>
</tr>
<tr>
<td>Environmental Risk Assessment (ERA)</td>
<td>Toxicity assessment of substances and chemicals.</td>
<td>(Wrisberg et al., 2002)</td>
</tr>
<tr>
<td>Multi Criteria Analysis (MCA)</td>
<td>Evaluation and comparison of different design alternatives under multiple criteria defined by the user.</td>
<td>(Wrisberg et al., 2002)</td>
</tr>
<tr>
<td>ECO Design Pilot (Product Investigation Learning and Optimization Tool)</td>
<td>Assessment of the environmental performance of the product on a web based platform. The tool identifies hotspots and then strategies for improvement can be suggested.</td>
<td>(Wimmer et al., 2004)</td>
</tr>
<tr>
<td>CES Selector with Eco Audit™</td>
<td>Tool for material selection that integrates functional, environmental and economic aspects of the product.</td>
<td>(Granta Design, 2013)</td>
</tr>
<tr>
<td>EcologiCAD</td>
<td>Environmental assessment of design alternatives in a CAD interphase.</td>
<td>(Leibrecht, 2008)</td>
</tr>
<tr>
<td>GABI DFX</td>
<td>Computer based tool to assess the performance of design alternatives considering compliance to regulation, environment, recycling and disassembly.</td>
<td>(PE-INTERNATIONAL, 2013)</td>
</tr>
<tr>
<td>Environmental Design Support Tool (EDST)</td>
<td>Tool that provides material and recyclability assessment. Design alternatives and strategies for improvement can be also compared.</td>
<td>(Yu et al., 1999)</td>
</tr>
</tbody>
</table>

**Indicators**

| ReSICLED model | Tool that can be used to evaluate end of life strategies and scenarios aiming to increase recycling and recovering rates of the product. | (Mathieux et al., 2008) |
| Environmental benchmarking | Environmental performance indicators that can be used compare products or design alternatives. | (Wimmer et al., 2004) |
| Material Intensity per Unit Service (MIPS) | Material and resource use indicator. | (Lagerstedt, 2003; Wrisberg et al., 2002) |
| Cumulative Energy Demand (CED) | Energy and resource use indicator. | (Huijbregts et al., 2010) |
| Oil Point Method (OPM) | Impact assessment indicator for estimating energy and resource use. | (Bey, 2000) |
| Environmental efficiency potential (E2PA) | Six environmental performance assessment indicators. | (Nagata et al., 2001) |

**Tools that identify and generate strategies**

<p>| Life cycle quality function deployment (LC-QFD) | Tool that assists the identification of improvement strategies derived from costumers’, environmental and legal requirements. | (Ernzer &amp; Birkhofer, 2005) |</p>
<table>
<thead>
<tr>
<th>Name of the tool</th>
<th>Short description</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>Environmental Quality Function Deployment (EQFD)</td>
<td>Tool that assists the identification of improvement strategies based on stakeholders’ requirements.</td>
<td>(Wimmer et al., 2004)</td>
</tr>
<tr>
<td>Eco Functional Matrix</td>
<td>Tool that assists the identification of improvement strategies by connecting the functional profile to the environmental profile of the product.</td>
<td>(Lagerstedt, 2003)</td>
</tr>
<tr>
<td>House of Ecology (HoE)</td>
<td>Tool that assists the identification of improvement strategies from an environmental and economic perspective based on stakeholders’ requirements.</td>
<td>(Halog et al., 2001)</td>
</tr>
<tr>
<td>Environmental Effect Analysis (EEA) or Environmental failure mode analysis (E-FMEA)</td>
<td>Tool that assists the identification of improvement strategies. It further provides comparison and prioritization of those strategies.</td>
<td>(Lindahl, 2000)</td>
</tr>
</tbody>
</table>

Numerous reviews of DfE tools are available in the literature that may assist practitioners to the identification and selection of suitable tools. See for instance: (Baumann et al., 2002; Birch et al., 2012; Bovea & Perez-Belis, 2012; Byggeth & Hochschorner, 2006; Luttropp & Lagerstedt, 2006)

Despite the apparent maturity and constant development of tools in literature, there is limited evidence of their systematic use in practice and their integration into product development processes. A number of obstacles and barriers have been reported, related both to the tools and the users or organizations that apply them. Tools have often been dismissed as time consuming due to for instance requirements on quantitative data, or as too complicated due to the terminology used, the outcome provided and the need of environmental expertise (Ernzer & Wimmer, 2002; Lindahl, 2005; Lofthouse, 2006; Millet et al., 2007). Additional obstacles for increased implementation have been reported (Lindahl, 2005; Pigosso et al., 2013), indicating a lack of:

- available competences and expertise in companies
- motivation on using such tools
- information on the available tools
- a systematic process for selecting tools

### 2.5.1 Selection of tools

Bhander et al. (2003) suggested that “product developers should be aware of the use and benefits of the broad range of ecodesign tools [before they begin to include environmental considerations as common-place practices] and be confident of choosing the most relevant tools for the job”. It is often the case however that companies have neither a structured process for selecting DfE tools nor the time or resources to perform investigations on the various tools available (Pigosso et al., 2013).

As Knight and Jenkins (2009) pointed out, many DfE tools “are not generic enough and thus not directly applicable to the product design processes”. Therefore, “selection and customization are essential activities in order for ecodesign tools to be successfully integrated into the design
process”. Likewise, Ritzen and Lindahl (2001), acknowledge that “careful selection of methods, customized methods and reflective implementation are key factors to reach a successful use of tools” and propose a conceptual model for tool selection. The model is illustrated in Figure 4.

![Figure 4 DfE tools’ selection procedure. Figure redrawn from Ritzen and Lindahl (2001)](image)

The suggested model is an iterative process that consists of various steps. The starting point is the establishment of a set of criteria that the tool should fulfil in order to make it relevant for the user. The selection of those criteria should take into consideration the users and preferably all different actors involved (that can be for instance people providing data). The next steps include the identification and evaluation of the tools according to the pre-established criteria while finally the most suitable tools are determined. Under the implementation process of the tools new needs and requirements may arise, therefore evaluation of the outcome and follow up of the process is suggested (Ritzen & Lindahl, 2001).

Based on the same principles, Knight and Jenkins (2009) have also proposed a model aiming to make DfE tools compatible and thus applicable to the product design stages that are intended to be used. Their model consists of five stages, illustrated in Figure 5.

![Figure 5 The applicability framework proposed by Knight and Jenkins (2009)](image)

Both models are developed with the aim to assist organizations and practitioners to select tools that are suitable and cover relevant needs of the design process. In addition to that, tool developers may also be assisted in order to provide already customised tools, which can be based on the requirements and needs of specific product categories.
2.5.2 Requirements on DfE tools

Research on DfE tools has identified a broad list of requirements that the tools need to fulfil in order to make them relevant to the product design and development process but also more useful to product designers. Such requirements can be classified as those related to the methodological and application aspects, to requirements related to the outcome of the tool, or other generic requirements. Table 3 summarizes the findings of previous studies in this area:

<table>
<thead>
<tr>
<th>Method and application</th>
<th>Outcome</th>
<th>Other</th>
</tr>
</thead>
<tbody>
<tr>
<td>Simple and easy to implement</td>
<td>Provide objective, valid and reliable results</td>
<td>Easy to find and obtain</td>
</tr>
<tr>
<td>Time efficient</td>
<td>Provide quantitative results</td>
<td>Low cost</td>
</tr>
<tr>
<td>Able to support decision making</td>
<td>Show the optimal direction to the designers</td>
<td>Low set up time requirements</td>
</tr>
<tr>
<td>Include terms that are easy to understand</td>
<td></td>
<td>User friendly</td>
</tr>
<tr>
<td>Promote work of multidisciplinary teams</td>
<td></td>
<td>Low education requirements</td>
</tr>
<tr>
<td>Be able to integrate into the product development process</td>
<td></td>
<td>Adjustable to different products and context requirements</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Easy to communicate benefits</td>
</tr>
</tbody>
</table>

Additional requirements, that make tools relevant from a DfE perspective have been also reported (Bovea & Perez-Belis, 2012; Byggeth & Hochschorner, 2006; ISO TR/14062, 2002; Lindahl, 2005; Lofthouse, 2006). These suggest that the tools should:

- have a life cycle perspective,
- identify and assess the most important challenges of the product,
- support decision making by prioritization of impacts or design strategies,
- be able to identify and handle trade off situations, and
- be suitable to use early in the product development process.

Although such generic requirements are very useful to consider, it should be also noted that requirements on DfE can be company, user, or even product specific. As stressed earlier tool selection is a critical point, for the successful application and adoption of the tool in the product development process of an organization. Issues related to the product per se, the structure of the product development process as well as the competences available become very important.

2.6 Factors affecting the successful integration of environmental aspects

The successful integration of environmental aspects into the product development processes depends on various parameters. Johansson (2002), compiled a list of internal and external factors based on a state of the art review of the related literature published at that time. The findings of this study are listed in Table 4 with some additional factors that were found in literature (Boks, 2006; Handfield et al., 2001; Ritzén, 2000; Ritzén & Beskow, 2001; Tingström, 2007; Umeda et al., 2012).
Table 4 Success factors for facilitating the integration of environmental aspects into product development.  
Table adopted and modified from Johansson (2002)

<table>
<thead>
<tr>
<th>Clusters</th>
<th>Success factors</th>
</tr>
</thead>
<tbody>
<tr>
<td>Management</td>
<td>Management commitment and support</td>
</tr>
<tr>
<td></td>
<td>Clear environmental goals</td>
</tr>
<tr>
<td></td>
<td>The environmental considerations are addressed as business issues and play a role in all business activities</td>
</tr>
<tr>
<td></td>
<td>Consider not only the operational dimension of ecodesign but also the strategic</td>
</tr>
<tr>
<td></td>
<td>Environmental issues are introduced when establishing a company's technology strategy</td>
</tr>
<tr>
<td>Customer relationships</td>
<td>Market research</td>
</tr>
<tr>
<td></td>
<td>A strong customer focus is adopted</td>
</tr>
<tr>
<td></td>
<td>Train their customers in environmental issues</td>
</tr>
<tr>
<td>Supplier relationships</td>
<td>Close supplier relationships are established</td>
</tr>
<tr>
<td>Development process</td>
<td>Environmental issues are considered at the very beginning of the product development process</td>
</tr>
<tr>
<td></td>
<td>Environmental issues are integrated into the conventional product development process</td>
</tr>
<tr>
<td></td>
<td>Environmental checkpoints, reviews, and milestone questions are introduced into the product development process</td>
</tr>
<tr>
<td></td>
<td>Company specific environmental design principles, rules and standards are used</td>
</tr>
<tr>
<td></td>
<td>Ecodesign is performed in cross functional teams</td>
</tr>
<tr>
<td></td>
<td>Ecodesign support tools are used</td>
</tr>
<tr>
<td></td>
<td>Good contacts among between departments about environmental issues</td>
</tr>
<tr>
<td></td>
<td>Good internal and external communication networks</td>
</tr>
<tr>
<td>Competence</td>
<td>Education and training are provided to the product development personnel</td>
</tr>
<tr>
<td></td>
<td>An environmental specialist supports the development activities — appropriate environmental expertise</td>
</tr>
<tr>
<td></td>
<td>Examples of good design solutions are utilised</td>
</tr>
<tr>
<td></td>
<td>Follow up studies; learn from previous experiences in a systematic way</td>
</tr>
<tr>
<td>Motivation</td>
<td>A new mind-set emphasizing the importance of the environmental considerations is established</td>
</tr>
<tr>
<td></td>
<td>Sustained motivation that arises from internal and external drivers</td>
</tr>
<tr>
<td></td>
<td>Presence of a so called “environmental champion”</td>
</tr>
<tr>
<td></td>
<td>Individuals are encouraged to take an active part in the integration of ecodesign</td>
</tr>
</tbody>
</table>

A conceptual model devised by Tingström (2007) classifies the different factors affecting the implementation of the DfE approach into four milestones namely: management, product development, DfE mind-set, DfE tools. In this thesis I refer to those areas as the main components for the establishment of a DfE strategy in an organization and as the facilitators for the successful implementation of the approach. More emphasis is given to the three latter ones, (the product development process, the DfE mind-set and tools) since managerial issues are not explicitly addressed in this work.
3 Methodology

This chapter presents the methods applied to collect information and analyse the results of Papers I and II. Three main methods are used: Case studies, literature review, and interviews. Table 5 indicates the methods that correspond to each of the two papers.

<table>
<thead>
<tr>
<th>Appended papers</th>
<th>Case study</th>
<th>Literature review</th>
<th>Qualitative research interviews</th>
</tr>
</thead>
<tbody>
<tr>
<td>Paper I</td>
<td>X</td>
<td></td>
<td>X</td>
</tr>
<tr>
<td>Paper II</td>
<td></td>
<td></td>
<td>X</td>
</tr>
</tbody>
</table>

3.1 Case study

A case study can be defined as “an empirical inquiry that investigates a contemporary phenomenon in depth and within its real life context” (Yin, 2009). Case studies are defined by interest in individual cases and can therefore be used to examine and analyse in detail specific examples or cases (Johansson, 2005). They are unique and have physical and social boundaries aiming to answer “how” or “why” questions. Case studies can be applied both in social and natural sciences while a variety of methods and strategies can be used in order to obtain results.

This thesis can be considered a case study on the vehicle manufacturing sector in Sweden since a sample of companies within these functional and geographical boundaries is investigated. The reason for selecting to work on specific case studies was the importance and value, as acknowledged in Paper I, of empirical data. Factors such as the type and size of company, the product per se, may have an influence on the successful integration of environmental criteria. By applying case studies methodology, internal and external factors that influence DfE implementation, in these specific companies are possible to be identified.

3.2 Literature review

Literature review includes the process of collecting, analysing, evaluating and summarizing scholarly material on a specific topic (Fink, 2010). Literature review has been used in both papers in order to collect information from previous publications. In Paper I the literature around DfE and recent developments within this particular topic was investigated to form the theoretical foundation of the paper and provide a reference point for the analysis and discussion of the results.

In Paper II, a more extensive and systematic review of the literature was performed serving as a stand-alone qualitative research method for that study. The aim of Paper II was to compile an inventory on the most commonly found methods and tools that can be used to facilitate the integration of environmental aspects into product development. Databases and library catalogues were examined in order to find relevant information in articles, conference proceedings, books, doctoral dissertations and reports. The searched terms included: ecodesign, ecodesign tools, DfE,
DfE tools, sustainable product design/development, environmental impact assessment methods/tools, life cycle assessment, simplified life cycle assessment etc. Due to the large amount of publications a screening process was performed to select the most relevant tools in primary or secondary sources. Primary sources are considered the ones that describe a specific method or tool (most times developed by the author), while as secondary, the ones that provided an overview or analysis of different tools. Finally, only tools for which sufficient information could be obtained were selected for further analysis.

The literature review resulted to 31 DfE tools. For the analysis of the tools a number of parameters derived from literature but also empirical studies were used. The detailed and comprehensive list of those parameters is presented in Paper II together with the strategy for analysis of the results.

3.3 Qualitative research interviews

Kvale (1996), defines research interviews as a conversation that has a structure and a purpose and where the reporter obtains information from the respondent. Different ways to perform interviews exist while the selection of the most appropriate one depends on the goals and scope of the respective study. For example interviews can be structured, semi-structured or open. Respondents can be interviewed individually, or in groups, face to face or from distance. Gillham (2005), highlights three characteristics of interviews that distinguish them from other type of methods e.g. questionnaires:

- the questions asked during interviews are open i.e. the respondents provide their own answer
- there is a form of structure and a purpose from the side of the interviewer
- there is a responsive or interactive relationship between the respondent and the interviewer that allows for some adjustments or clarifications

Qualitative research interviews and more specifically semi-structured interviews were selected as the main method for data collection in Paper I. Semi structured interviews were selected in order to increase understanding and describe the practices that are currently implemented in the selected companies (Kvale & Brinkmann, 2009).

Eighteen interviews were performed with four different vehicle manufacturers in Sweden that produce road, rail vehicles and vehicle components. These companies were selected in order to acquire a broad overview of the sector and also to obtain a range of values in terms of market, end-customer and regulatory requirements. Initially the target group in each company was personnel with environmental as well as (DfE) tools’ expertise. The authors had one contact person with environmental expertise in each of the companies. This person then assisted in finding the rest of the interviewees, a process known as “snowball sampling”. The sample of environmental and (DfE) tool experts covered different working profiles and roles that can be found in the studied companies, thus aiming to illustrate how DfE is organized in the respective company. At a later stage vehicle design engineers were approached as well, in order to get additional insights and test for any potential bias of the environmental experts. Previous
interviewees assisted in finding contact people. Although different people were approached, one person from each company was finally interviewed. The process of interviews was completed when saturation of the responses (per company) was reached. The sample of the respondents can be found in Table 6.

The sample of design engineers in this study is obviously small, compared also to the large number of employees in these companies. Nevertheless, it can be claimed to be satisfactory for this specific study. The goal of this study is to get an overview of the current practices and collect facts, rather than to map how DfE is implemented in each engineering unit where the need for a bigger sample size would have been suitable.

Table 6 Respondents participated in the interview study
(for a more detailed list of the profiles of the interviewees see Paper I)

<table>
<thead>
<tr>
<th>Company</th>
<th>Interviewees</th>
</tr>
</thead>
</table>
| Company A | Senior specialist for environmental features  
Feature leader for materials and environment  
Environmental engineer - LCA consultant  
Environmental consultant - process manager  
Engineer designer |
| Company B | Strategic advisor for the core value of environment  
Attribute leaders for environment (2)  
System engineer |
| Company C | Senior engineer on vehicle verification and environmental regulation  
Group manager - product designer |
| Company D | Manager for centre of competence on Design for Environment (DfE)  
DfE engineers (5) – in two different departments of the company  
System engineer |

To prepare and perform the interviews, the stepwise methodology described in the handbook by Kvale and Brinkmann (2009) was followed. A list of pre-defined questions was developed, although these left opportunities for open discussions with the interviewees. The respondents received an introductory document for the study but not the exact questions. However, a brief background was also given to them before the interview process. The majority of interviews were performed face to face and lasted for approximately fifty minutes. Only in two cases a telephone interview was arranged due to distance and time constraints. The interviews were recorded and later transcribed word by word. Respondents had the possibility to see the transcribed text, verify the content and indicate possible confidential issues. For the analysis of the results, the transcribed material was classified into different themes and clusters derived from the research questions as well as patterns observed in the text (Miles & Huberman, 1994).
4 Summary of results and discussion

This chapter summarises and discusses the findings of Paper I and II that are appended in this thesis. The structure of the chapter corresponds to the research questions posed in the beginning of this cover essay, where the paper or papers that address this question are indicated. Each section includes a subsection that highlights the contribution of the results to the overall aim of this thesis. The chapter concludes by reflecting on the research strategy and methodology followed in this work.

The aim of this thesis was to investigate the ways that environmental constraints can be efficiently integrated into product development processes in order to assist in improving the environmental performance of products from a life cycle perspective. Special focus has been given to the development and utilization of DfE tools as a way to support such integration. It should be also noted that this work aims to provide the foundations towards the development of a comprehensive multi-criteria approach that may assist vehicle designers to integrate environmental considerations into their everyday practices. For this reason understanding the processes and tools that are already in place for the studied companies is of paramount importance. Then opportunities, barriers and needs for the successful and increased use of such tools can be illustrated.

4.1 Integration of environmental aspects during vehicle design and development

The ways that environmental aspects and requirements are introduced during vehicle design stages are investigated and discussed in Paper I. Information was obtained through semi-structured interviews with personnel from various disciplines and positions in the companies (see Table 1 in Paper I to obtain more information on the profiles of the interviewees). First, the questions posed to the respondents were related to the processes and people involved for facilitating the integration of environmental aspects in product development. Next, information regarding the actual environmental constraints and requirements that are prioritised during that process was requested, as well as the factors that drive such prioritization.

4.1.1 People and processes

In relation to the ways that the studied companies incorporate environmental aspects into the product development process, three main approaches were encountered. It should be first noted that all four companies have a formal product development process in place and at least one group of people that is responsible for environmental related issues. In practice, the roles of those specialists varied as did their responsibilities and extent of their involvement during product development processes. This diversity was first observed during the process of preparing the interviews and is illustrated in the working areas of respondents described in Paper I.

The encountered approaches vary from systematic and continuous involvement of environmental experts throughout product development to a more prescriptive approach where requirement
selection and monitoring are performed more centrally in the company with less interaction with
the vehicle design departments and actual product development processes. More specific, three
of the studied companies have established systematic ways to organize and facilitate DfE work.
In two of these companies DfE is an integrated process where environment is considered as one
among the different features of the product during the decision making processes. In the other
one, DfE is organized centrally by a group of experts that are responsible for the environmental
performance of the product and who are also actively involved into product development
projects. A different approach was encountered in the fourth company where little interaction is
reported with the vehicle development groups in terms of selection of environmental priorities
and support during design decisions. The major role of the environmental experts (who are
located centrally in the company) is to monitor regulation, to communicate the requirements to
product development groups and also verify the compliance of the product to those
requirements. In all three approaches designers have the responsibility to consider environmental
aspects during their everyday work.

After analysing the obtained results, Paper I concluded that the various practices have led to
different success and maturity levels of DfE implementation while a number of internal barriers
and inconsistencies with the literature were identified. As already discussed, although all four
companies have formalised processes for product development, similar formalised structures
regarding the integration of environmental aspects were not always met. Environmental expertise
and competence is available in the studied companies and has the potential to drive the diffusion
and implementation of the DfE principles by taking actively part and supporting the product
development groups. In many cases however, they have a more advisory or prescriptive role and
they are not always participating in product development projects. These observations may
contradict with the DfE principles and success factors that promote multi-disciplinary teams
(Lindahl, 2005), integrated and structured processes (Tingström, 2007), and environmental
aspects to be a natural part of these (ISO TR/14062, 2002; Tingström, 2007). For most
companies the process of systematically assessing, monitoring and integrating environmental
requirements into product development, either by an established environmental department or by
the vehicle engineers themselves, was something relatively new. Thus processes, responsibilities,
environmental requirements, and information requirements are not yet totally coordinated. This
often leads to inefficient processes, lack of communication and in some cases reluctance for
cooperation between “proponents” and “executors” of DfE strategies (as they are defined by
Boks (2006)). Paper I showed that the identified limitations often reduce the possibilities for
proactive work and considering environmental aspects during the early stages of product
development as suggested by numerous authors (Bhamra, 2004; Johansson 2002; Luttropp &
Lagerstedt, 2006; Tingström, 2007).

Various ways to improve the current situation, increase the systematic integration of
environmental aspects during vehicle design, overcome the identified barriers and bridge the gap
between theory and practice have been suggested in Paper I. The majority refer to harmonization
of DfE processes among the different units and departments of the companies as well as
increased education and training on DfE routines (Johansson 2002; Ritzén, 2000).
4.1.2 Environmental challenges and requirements

Despite the different DfE practices adopted and discussed above, Paper I showed that vehicle manufacturers are aware of the challenges that their industry needs to face. Their attention on how to overcome those challenges and minimize their environmental impact draws on similar aspects. Improving energy efficiency during the operation stage, minimizing the emission levels of regulated pollutants, controlling the use of hazardous materials and substances and improving recyclability are the major focus areas. Product specific priorities were also identified based on customer demands or voluntary requirements of the company. A summary of the environmental constraints discussed in Paper I is displayed in Table 7.

<table>
<thead>
<tr>
<th>Environmental constraints</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Production</strong></td>
</tr>
<tr>
<td>Hazardous materials, substances and chemicals</td>
</tr>
<tr>
<td>Emissions during production processes</td>
</tr>
<tr>
<td><strong>Resource constraints</strong></td>
</tr>
<tr>
<td><strong>Operation</strong></td>
</tr>
<tr>
<td>Energy use (fuel consumption)</td>
</tr>
<tr>
<td>Emission of pollutants</td>
</tr>
<tr>
<td>External noise</td>
</tr>
<tr>
<td>Air quality in the vehicle</td>
</tr>
<tr>
<td><strong>End of life</strong></td>
</tr>
<tr>
<td>Recyclability of parts and materials</td>
</tr>
<tr>
<td>Vehicle recycling</td>
</tr>
</tbody>
</table>

Similar to other sectors, as showed by Bey et al. (2013), Boks (2006) and numerous other authors, the vehicle manufacturing companies studied here, are continually working to meet legal and customer demands. These demands were reported among the major drivers for selecting and prioritizing environmental requirements but also as the enablers in many cases for the successful incorporation of environmental aspects into the design and development process.

Based on the DfE principles, organizations need to be able to identity and prioritise aspect that are relevant to consider, taking into account all life cycle stages and value chain of the product (ISO TR/14062, 2002; Johansson 2002). An important observation from Paper I was that a life cycle perspective was not always integrated into design decisions. Great emphasis is given to minimize the impact during the use phase which is of course the most significant impact of today’s vehicles from a life cycle perspective. Issues related to acquisition of raw materials, their production processes and the associated impacts are not always addressed. From a DfE and life cycle perspective this may lead to sub-optimizations, if design alternatives are not considered in a holistic and systematic way. For the sustainable development of the sector there are significant risks, if emerging challenges and trade-offs are not properly addressed.

4.1.3 Contribution to the aim of the thesis

The findings from this research question assisted to fulfil the aim of this thesis and increase understanding on the ways that DfE is organized in the studied companies. In relation to the success factors identified in literature, best practices but also areas for improvement were
identified indicating ways that DfE can be more efficiently implemented. Additionally, the environmental aspects that are prioritized by the studied companies were addressed, providing useful information in order to answer the third question of this thesis and evaluate whether DfE tools that are available in literature today, manage to capture aspects that are of importance for vehicle designers.

4.2 The utilization of DfE tools

The use of supporting tools is very common during the product development processes and especially for the integrated product development models (Lindahl, 2005; Tomiyama et al., 2009). Dialogue based tools (such as brainstorming or mind maps) as well as quantitative tools (simulations) and design tools (CAD tools) can be found. In this work the use of a specific type of tools is investigated. These tools provide information and support regarding the environmental performance of the product and may originate from environmental as well as design sciences as discussed in Paper II.

The utilization of DfE tools in vehicle manufacturing industries in Sweden was investigated in Paper I. Interviewees were asked about the type of DfE tools used in their company as well as the ways that such tools are integrated into the product development process.

4.2.1 The use and integration of DfE tools in the studied companies

Paper I showed that the vehicle manufacturing companies studied in this thesis use or have used different types of DfE tools and for a variety of purposes:

- to generate ideas during product planning,
- to provide support to designers with the establishment of eco-design guidelines,
- to monitor compliance with certain requirements, and
- to evaluate the environmental performance of a product, technology or design solution

The list of tools mentioned by the respondents is displayed in Table 8. Shaded areas in the table indicate the tools that are currently available in the respective company and used in a systematic way. Non-shaded areas indicate that the tool is not available at the moment or that the utilisation level of the tool varies.
Table 8 List of tools mentioned by the interviewees from the four studied companies

<table>
<thead>
<tr>
<th>Type and name of tool</th>
<th>Company A</th>
<th>Company B</th>
<th>Company C</th>
<th>Company D</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Mapping and generating ideas (product planning)</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
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<tr>
<td>Brainstorming</td>
<td></td>
<td></td>
<td>√</td>
<td>√</td>
</tr>
<tr>
<td>Mind maps</td>
<td></td>
<td></td>
<td></td>
<td>√</td>
</tr>
<tr>
<td>Customer surveys</td>
<td>√</td>
<td></td>
<td></td>
<td></td>
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<tr>
<td><strong>Guidelines and checklists (product development and product design)</strong></td>
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<tr>
<td>Environmental design guidelines</td>
<td>√</td>
<td>√</td>
<td>√</td>
<td>√</td>
</tr>
<tr>
<td>Recyclability checklists (DfR)</td>
<td></td>
<td></td>
<td></td>
<td>√</td>
</tr>
<tr>
<td>Substance and chemical control lists</td>
<td>√</td>
<td>√</td>
<td>√</td>
<td>√</td>
</tr>
<tr>
<td><strong>Performance indicators (product planning, development and design)</strong></td>
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<tr>
<td>Benchmarking</td>
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<td></td>
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<tr>
<td>EPS indices</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Recyclability indicators</td>
<td>√</td>
<td></td>
<td></td>
<td></td>
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<tr>
<td>Eco-footprint</td>
<td></td>
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<tr>
<td>Vehicle performance indicators</td>
<td></td>
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<td></td>
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<tr>
<td><strong>Databases (product design and detailed development)</strong></td>
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<tr>
<td>Material database systems</td>
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<td></td>
</tr>
<tr>
<td><strong>Tools for impact assessment (product development and detailed design, complete product)</strong></td>
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<td></td>
<td></td>
</tr>
<tr>
<td>LCA / SLCA</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>EIA/E-FMEA</td>
<td></td>
<td></td>
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<td></td>
</tr>
<tr>
<td>LCC</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Communication tools (complete product)</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>EPD</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Testing and verification (product development, complete product)</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Simulations / Laboratory testing</td>
<td></td>
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</tbody>
</table>

DfR= Design for recycling; EPS=Environmental priorities strategies; LCA=Life cycle assessment; SLCA=Simplified life cycle assessment; EIA=Environmental impact assessment; E-FMEA=Environmental failure mode effect analysis; LCC= Life cycle cost analysis; EPD=Environmental product declaration.

Paper I showed that different types of DfE tools are available in the toolbox of the different companies, although only a few are currently used in a systematic way. Monitoring tools such as material checklists and substance control lists are among the most systematically applied tools. These tools are based on sector-specific initiatives and are adopted by all studied companies through their participation in joint industrial platforms or through the development of internal customised tools and processes. They provide a list of all restricted and prohibited substances and materials that vehicle manufacturers need to consider thus enabling vehicle manufacturers to monitor the compliance of their product to regulatory, costumer and corporate requirements. For this reason material checklists need to be applied early during product design. Their utilization however, requires the coordination of multiple stakeholders including vehicle engineers, suppliers as well as purchasing departments.

Recyclability indicators and material databases are also among the most commonly applied tools that are either customised by the company or based on sector standards and guidelines. Both tools provide information about the materials that constitute the product and are used to monitor the regulatory and corporate targets and requirements.

When it comes to the use of analytical tools (e.g. environmental assessment methods) variations among the studied companies were observed. Thus, the experience and maturity level with regard to the development and use of such tools differs significantly among the studied companies. Only two companies consider LCA a systematic tool used in the organization. In general,
analytical tools are considered advanced tools and therefore are used centrally in the studied companies by tool experts or external actors. Results from analytical tools have an advisory role during product planning and design decisions.

Paper I concluded that despite the rich variety of DfE tools available in the literature (as presented in Table 2 in section 2.5 of this thesis), vehicle manufacturers at present use prescriptive tools (monitoring lists) in a more systematic way while the need and integration of analytical tools is not always obvious and less systematic in practice. A holistic and systematic assessment of the environmental performance of the product however, would increase the possibilities for improvements, especially in times when advance technologies and materials are emerging and environmental challenges are increasing.

4.2.2 Limitations and needs

The use of tools comprises an important part of DfE approach. As pointed out by Hallstedt (2008), tools provide methodological support but may also assist in learning processes and increase cooperation among the users (Tingström, 2007). As already shown, tools that may enhance and support learning and cooperation in the studied companies are not used in a systematic way. Therefore limited evidence exist that tools with such possibilities are used by multidisciplinary teams as suggested by Lindahl (2005). Analytical tools for instance are used by tool experts. Vehicle designers on the other hand do not have the possibility to get direct information on the environmental effect of their design solutions. Simplified analytical tools and design guidelines which were developed to be implemented during the product design processes are not currently in place.

After analysing the obtained results, the author identified a need for a more systematic use of tools and especially tools that would assist learning processes and increase cooperation during design stages. The optimal solution is not necessarily that design engineers should have the responsibility for implementation and use of advanced DfE tools. However, tools or processes that increase designers’ engagement and integrate environmental and technical aspects in a comprehensive and reliable way would be beneficial. For these tools to become effective they need to cover aspects that are relevant for the company and product designers, and perhaps even more important; they need to cover aspects that are accessible. It is also important that the tools for DfE are not an additional load in the design and development process but rather show similarity to or can easily be integrated into already existing design tools within the company. Although a small sample of vehicle designers participated to the interview study in Paper I, both them and the environmental experts, acknowledged that tools that would manage to integrate environmental information with other requirements considered during the design phase, would be of interest.

4.2.3 Contribution to the aim of the thesis

Research regarding the use of DfE tools is of great importance for the overall aim of this thesis and PhD project. By investigating the tools that are currently in use, valuable information is obtained on what makes a tool relevant and useful for the studied companies, what constraints
may arise and what needs can be identified. The latter provided input to the research performed in Paper II.

4.3 The potential of existing tools to be used during vehicle design

Selection and customization of tools based on the needs of the company and the user has been acknowledged by many authors as factors that would determine the efficient and successful use of tools (Bhander et al., 2003; Pigosso et al., 2013; Ritzen & Lindahl, 2001). Despite the numerous literature reviews of DfE tools that are available, only a few of these studies examine the applicability of tools in certain product categories. Unger et al. (2008) for instance, have looked at the suitability of ecodesign tools for electrical and electronic equipment. The potential of existing DfE tools to be applied during vehicle design processes is addressed in this thesis and specifically in Paper II.

Based on a systematic review of the literature, 31 DfE tools were identified, listed and analysed. The scope of the paper included prescriptive, analytical and tools that generate design strategies. The results from the interviews performed in Paper I as well as previous research (presented in section 2.5.2.) assisted the compilation of a set of parameters and requirements that could increase the potential of DfE to be used during product development processes in general and vehicle design processes in particular. These parameters serve as the basis for analysis of the identified tools in Paper II and reflect both to methodological characteristics as well as vehicle design requirements. A short summary of the vehicle design related parameters is presented in Table 9. For a more comprehensive presentation the reader may refer to Table 1 and Table 2 in Paper II.

Table 9 List of parameters used to evaluate the potential of DfE tools to be applied during vehicle design

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Short description</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Systems perspective</strong></td>
<td></td>
</tr>
<tr>
<td>Environmental aspects</td>
<td>Including environmental challenges that are relevant from a vehicle design perspective while not limiting the possibilities to identify future challenges.</td>
</tr>
<tr>
<td>Life cycle stages</td>
<td>Considering the life cycle of the product and especially the stages of vehicle manufacturing, operation and end of life.</td>
</tr>
<tr>
<td><strong>Multi-criteria approach</strong></td>
<td></td>
</tr>
<tr>
<td>Possibilities to integrate</td>
<td>Integrating and monitoring regulation requirements to ensure the compliance of a design solution.</td>
</tr>
<tr>
<td>regulation requirements</td>
<td>Integrating and considering functional constraints in order to provide feasible design solutions but also to offer the possibilities to identify the trade-offs that may occur from conflicting aspects.</td>
</tr>
<tr>
<td>Possibilities to integrate</td>
<td>Integrating and monitoring stakeholders’ requirements and especially customer demands.</td>
</tr>
<tr>
<td>functional requirements of the product</td>
<td>Integrating and considering the economic performance of the suggested alternatives or design solutions</td>
</tr>
<tr>
<td>Possibilities to integrate</td>
<td></td>
</tr>
<tr>
<td>stakeholders’ requirements</td>
<td></td>
</tr>
<tr>
<td>economic requirements</td>
<td></td>
</tr>
<tr>
<td>Possibilities to integrate</td>
<td></td>
</tr>
<tr>
<td>Integration to the design process</td>
<td>Engaging engineer designers and provide them with direct information of the environmental risks and benefits associated to their design solutions by integrating DfE tools to existing engineering tools.</td>
</tr>
<tr>
<td>Possibilities for integration with other tools (e.g. engineering design tools)</td>
<td></td>
</tr>
</tbody>
</table>
Paper II showed that a variety of DfE tools exist that have the potential to evaluate the environmental performance of vehicles and assist product designers to identify improvement strategies from a systems perspective i.e. by considering environmental impacts that are of relevance to vehicle design as well as all life cycle stages of the product. These tools can be qualitative or quantitative, leading to different complexity levels (in terms of environmental expertise and data needs) but also quality of the outcome. Data complexity and reliability of the outcome is a common trade-off that tool practitioners need to consider, which in combination with the “design paradox” discussed before, limits the potentials of quantitative tools (e.g. the MET matrix or streamlined LCA tools) to be efficiently applied in product planning stages. By the time sufficient information is obtained that would provide a robust outcome, modification possibilities might no longer be feasible.

Data availability is a major limitation mostly for advanced analytical tools (e.g. LCA) where detailed knowledge on design parameters of the product is required (Birch et al., 2012; Byggeth & Hochschorner, 2006; Lofthouse, 2006; Millet et al., 2007). Paper I showed that in the studied companies where analytical tools are systematically applied, efforts to integrate and use information obtained from other tools established in the company are initiated (e.g. the combination of LCA to material databases). This has reduced constraints related to data and time (Dahllöf L., 2013) and provided greater potentials for tools to be applied early in the development process. Considering the availability of environmental expertise in all of the studied companies (most of them experienced on DfE tools) obstacles related to competence of advanced tools can be reduced.

The development towards tools that do not consider environmental aspects as an isolated feature of the product but manage to combine this information with other aspects (such as functional or economic) is increasing (Bovea & Perez-Belis, 2012; Halog et al., 2001; Lagerstedt, 2003). Paper II concluded that it is most often tools that identify and generate strategies, which offer such possibilities and manage to integrate aspects and requirements that are of relevance during vehicle design. Most of these tools cover two to three aspects at the same time while various combinations are available. EQFD and HoE for instance combine environmental parameters with stakeholders’ requirements while the Eco-Functional Matrix combines environmental to functional properties of the product. These tools can be used as a roadmap to vehicle designers during the product planning stages. To increase the potential of those tools however, support from analytical tools is necessary (Birch et al., 2012; Bovea & Perez-Belis, 2012). The use of EEA in combination with LCA for instance was investigated by (Tingstrom & Karlsson, 2006). Analytical tools that integrate a multi-criteria perspective were available as well although fewer. Paper II provides examples of such tools (e.g. the CES Selector with EcoAudit) that manage to integrate functional aspects or regulatory requirements with a simplified environmental assessment process.

The final aspect for assessing the effective use of DfE tools within vehicle design is related to the integration possibilities of DfE tools with engineering design tools. Although a development towards software tools is observed their integration to design tools is still limited. A few of the tools listed in Paper II have been designed to be connected to or utilize models that design engineers may use (CAD models for instance). Due to the complexity of the product however
there is a great challenge for tool developers to facilitate such integration of tools in a reliable and efficient way.

It can be concluded that, despite the identified limitations of existing tools, vehicle designers have a rich and diverse toolbox from which suitable tools can be selected based on their needs and available competences. There is no single tool that manages to fulfil all criteria and requirements of the users. Therefore it is recommended that a combination of tools is applied and at different stages of the product development stage. To some extent this is applied already today although different processes and maturity levels among the studied companies were identified. The development of tools that integrate analytical processes with strategy identification and selection is recommended in order to make them more relevant and applicable to vehicle design and also assist to bridge the identified communication gaps and enhance learning processes. Increased integration of a multi-criteria perspective in those tools would facilitate their use not only during vehicle design but during product design processes in general.

4.3.1 Contribution to the aim of the thesis

This research question fulfils the aim of this work by illustrating how and to what extent the existing DfE tools can be supportive during vehicle design processes by providing useful information and covering aspects that are of relevance for the studied companies. Limitations of existing DfE tools are indicated that may provide useful information for the development of a multi-criteria approach aimed in the PhD project.

4.4 Reflection on the research strategy and methods

The research strategy selected for this work is based on qualitative methods. Case study, interviews and literature review have been used in order to obtain results for the specific research questions. The motivation behind this selection is that the aim for this work was to collect empirical data and increase understanding on the processes that are currently in place among a specific industrial sector. To be able to analyse the results obtained from the interviews, knowledge on the principles and evolution of this research area was need. Especially for the development and availability of DfE tools state of the art data were of interest.

A number of strengths and weaknesses associated to the selection of this research strategy have been encountered. Although multiple suggestions for improvement and development of the current work can be identified (some are listed in the next section), it can be overall concluded that the selection of this research strategy provided the author with relevant answers to the research questions posed.

Case studies

Various experts in the area of DfE point out that, company specific factors are expected to influence the successful integration of the DfE approach into product development to a great extent (Boks & McAloone, 2009). Case studies can be of help to understand and specify such factors. The interest in case studies and specifically in looking at the vehicle manufacturing industry in Sweden was also due to the author’s involvement in the centre for ECO² vehicle
design that is specialised in research on vehicle design and has a close cooperation with vehicle manufacturing industry.

The advantage with the Swedish vehicle manufacturing industry was that a diversity of products were able to be studied covering all transport modes that are under the scope of the centre for ECO² Vehicle Design. A major limitation with such a specialization however, is the fact that results may not easily be generalised for other sectors and product groups or even for other organizations within the same sector but of different geographical boundaries and cultures. Although our intention from the beginning was not to generalise results for other sectors and product categories, the lessons learned from these industries may assist in bridging the gap between methodological development and practice around DfE.

**Interviews**

The aim of this work was to gain insight and explore current practices that are implemented in the vehicle manufacturing industry in Sweden, which in turn makes research interviews a suitable method. Among the strengths of this method is that current and up to date data were collected. The obtained results however need to be validated, a process that is more difficult to define in qualitative studies (Creswell & Miller, 2000). Validation of the results from the interviews has been performed through different steps and processes:

- By identifying relevant people for the interviews since key actors involved into the DfE process of each company were approached.
- After the interviews respondents had the opportunity to look the transcribed material and verify the content ensuring that the right material is analysed.
- Analysis was performed based on methodologies obtained from the literature.
- During the analysis of the transcribed material, the responses of the employees of the same company were compared to ensure coherence. The results are not expected to vary since no conflicting issues were identified.

The validity of the researcher’s interpretations has been also assessed in different ways; through analysis of the results with senior researchers and supervisors, through the engagement to the centre of ECO² Vehicle Design and dissemination of results among vehicle related companies and researchers, and finally through the participation to international scientific conferences where the results of this work were presented.

**Literature review**

Literature reviews provide the possibility to obtain state of the art information on the research topic by covering a significant number of publications available in different formats (scientific journals, conference proceedings, books and dissertations). The main drawback with such approach is the large number of publications available that increases the possibilities that important publications are not reached and therefore not considered. It has been already acknowledged that omissions in our compilation of DfE tools are expected. It can be claimed
however that representative examples are given for each tool category as well as references for further consultancy. Increasing the amount of tools would increase the risk that results become less comprehensive, hence limiting the possibilities for in depth analysis of the tools.
5 Concluding remarks

This chapter presents the main conclusions of this thesis and highlights the contribution to the area of DfE.

5.1 Main conclusions

The overall aim of this work was to investigate the ways that environmental aspects and requirements can be efficiently integrated into product development processes in order to assist in improving the environmental performance of products from a life cycle perspective. Special focus has been given to the processes as well as the development and utilization of tools that can support such integration. This thesis looked specifically into vehicle manufacturing industries and the integration of environmental aspects and the use of DfE tools during vehicle design. In relation to the research questions posed in the beginning of this thesis the main conclusions can be summarised as follows:

- **RQ1: Which environmental aspects and requirements are prioritized today by the vehicle manufacturing industry in Sweden and how are those aspects integrated into product development processes?**

  The studied companies have adopted different ways to identify and integrate environmental aspects into their design stages. Three main approaches were encountered that vary from integrated to prescriptive practices, therefore leading to different success and maturity levels. Vehicle manufacturers are aware of the challenges that they need to address, although in most cases a compliance model is adopted with limited proactive work in regards to the environmental requirements introduced into the product design stages. Among the most important aspects prioritised during product development activities include: energy efficiency, reduction of emissions, toxic or other hazardous materials or substances, recycling aspects, as well as external noise. Although similar, these aspects are weighted differently among the different transport modes studied.

- **RQ2: What types of supporting tools are utilized by the vehicle manufacturing industry in Sweden? What limitations and needs can be identified with regard to the current use of tools within the studied companies?**

  In relation to the use of DfE tools this study showed that tools that manage and monitor environmental regulations (e.g. substance and chemical control checklists) have succeeded to become a part of the routines during the product development process and are systematically used by all companies. On the other hand, the utilization of analytical tools or environmental design guidelines is less formalised and less frequent in practice. Different maturity levels exist in relation to the development and use of tools. A need for tools that enhance communication between environmental experts and designers is addressed. To fulfil that, tools need to be harmonised across the company and include aspects that are relevant for all actors. A multi-criteria approach is suggested that includes features of the product that are relevant from a DfE as well as vehicle design perspective.
- RQ3: Do the tools that exist already in literature contain features that have been identified as important to be able to support vehicle design? What aspects are covered and what is missing from a vehicle design perspective?

A variety of DfE tools are available that provide a rich and diverse toolbox in order for environmental aspects to be successfully integrated into product development processes. These tools vary between prescriptive, analytical (simplified or advanced) or tools that identify strategies. Tools that have the potential to support vehicle design processes are available; for example material checklists, energy and material indicators, advanced analytical tools (e.g. LCA or LCC) and tools that generate strategies. The main limitation of existing tools is the lack of integration to the design process and the lack of systematic inclusion of other aspects that may be relevant during vehicle design (e.g. functional aspects). A need towards the development of tools that assist vehicle or product designers in general to make informed and comprehensive choices based on a variety of requirements associated to the product is identified.

5.2 Contribution to the DfE research area

To this end the contribution of this thesis to the DfE area can be discussed. As already mentioned, the results obtained from Paper I should not be generalized, however a few concluding remarks relevant for other sectors and product categories may be introduced.

- Paper I provides empirical data in order to bridge the identified gap between methodological development and the implementation of the DfE approach. Evidence is provided that maturity in relation to DfE implementation varies even for companies within the same sector that face similar challenges. By introducing the various approaches and practices, additional examples to the ones that exist already in literature are provided. Based on the identified obstacles and needs it became apparent that there cannot be a single solution for all companies. Efficient implementation of the DfE approach should rather be based on customised recommendations. The results further highlight that more empirical studies are needed that look in different sectors and product categories.

- The work performed in this thesis provides information on the diffusion and maturity of DfE tools in industry. It lists DfE tools that are applied in certain companies and provides insights on what makes tools successful, what barriers may arise and what opportunities exist with those tools.

- Throughout this thesis, DfE was looked upon as an integrated framework acknowledging that processes, people and DfE tools are all important components of it. Most studies have been looking at these components separately. This thesis shows that relationships among these components exists and that empirical studies investigating DfE implementation in holistic way may obtain useful results and increase understanding on the barriers and success factors for the efficient adoption of DfE strategies and tools.

- Finally, this thesis and second paper appended may assist product developers and practitioners of DfE tools to identify the ones that fulfil their needs and make informed choices when selecting a DfE tool. In this respect, support to product designers is
provided by offering a compilation of tools to choose from. The target group of Paper II is vehicle manufacturing companies although the findings can be considered relevant to more product categories and sectors.
6 Future work

6.1 Development of current work

The results presented in this thesis indicated that the practices adopted and the overall maturity the DfE approach varies significantly among the studied companies. Differences were encountered not only among the different companies but also among departments of the same company, indicating that a systematic DfE approach is not established yet. Paper I lists a number of barriers and limitations that in their majority were related to the internal processes in the organization but also to the lack of efficient communication and understanding of the actors involved in the DfE process. Of special interest is therefore to understand how the executors of DfE requirements (vehicle designers and engineers) perceive DfE processes. It also has to be considered that different departments may weigh environmental aspects differently or be affected by environmental requirements to different extents.

The research strategy adopted so far did not allow any active participation of the researcher into those processes. Moreover, low diversity in departments and units approached in the first paper did not provide with details on how different departments and units of the same company work with DfE. To increase understanding on such variations and to map the current situation in different units in one or several organizations additional interviews could be performed. Action research i.e. participation of the researcher to actual projects and decision making processes may provide useful insights on the drivers and barriers for the systematic and life cycle based considerations of environmental aspects.

In relation to the use and adoption of tools similar studies can be performed that may assist in increasing the use and adoption of DfE tools in industries. However, different needs can be identified due to the differences in experience and utilization of tools. For the companies that have such experience, there is a need to look at the processes of integrating tools with design practices and also for increasing the efficiency of how the outcome obtained from such tools is used. In the cases with low tool utilization, there is a need to assist into establishing the processes and information networks, capacity building and education but most importantly selecting the tools that are of major benefit for the organizations. Continuation of the work performed in Paper II with case studies that test different tools on current and future products could provide useful insights.

6.2 Towards a multi-criteria design optimization approach

As already mentioned this thesis is part of a PhD program which aims to provide product designers and specifically vehicle designers with a comprehensive material selection framework. The research strategy and suggestions for future work are illustrated in Figure 6.
The input provided from this thesis assisted in increased understanding of the practices that are currently in place as well as on the aspects that would increase the interest of vehicle designers on DfE tools. To develop this research further and bearing in mind the goal of this PhD project, a number of research opportunities can be identified. First, there is a need to understand the environmental constraints that may occur when new materials and design structures are introduced into the product system and how such constraints can be assessed. This can be done through case studies where a variety of DfE tools are used to compare current and future design solutions. Such studies may not only illustrate the environmental aspects that need to be considered and prioritised but may also assist to evaluate the applicability of tools in practice (advancing the work performed in Paper II). Later on, economic as well as functional and other criteria relevant for vehicle designers (as discussed in Paper II) will be integrated to the suggested multi-criteria framework. Testing the suggested framework into real decision making situations and customizations based on the needs of the user is essential in order to derive its final form.
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