



**KTH Architecture and
the Built Environment**

Assessing design strategies for improved life cycle environmental performance of vehicles

Sofia Poulikidou

DOCTORAL THESIS
in Planning and Decision Analysis
with specialization in Environmental Strategic Analysis

Stockholm, Sweden 2016

Title: Assessing design strategies for improved life cycle environmental performance of vehicles

Author: Sofia Poulikidou

Email: sofiapo@kth.se

KTH Royal Institute of Technology

School of Architecture and the Built Environment

Department of Sustainable Development, Environmental Science and Engineering

Division of Environmental Strategies Research – fms

Centre for ECO² Vehicle Design

TRITA-INFRA-FMS-PHD 2016:04

ISBN 978-91-7729-108-4

Printed by US-AB in Stockholm, Sweden 2016

Preface

This thesis provides a summary of the research work performed during the five year PhD program of “Planning and decision analysis – with specialization in Environmental Strategic Analysis”, at the Division of Environmental Strategies Research (fms) at KTH.

This research was conducted within the research project “Coupling Materials-Environmental Analysis” funded by the Center for ECO² Vehicle Design. The center provides a node for multidisciplinary research on different features of vehicle design incorporating research both on road and rail vehicles. Among the aims of the center is to balance the ECOnomical and ECOlogical (ECO²) constraints of vehicle design and provide methods and tools for functional and environmentally improved transport solutions and designs. Two academic units at KTH (the Department of Aeronautical and Vehicle Engineering, and the Division Environmental Strategies Research (fms)), vehicle related manufacturing industries and transport authorities in Sweden were among the core partners of the center.

The research project “Coupling Materials-Environmental Analysis” consists of three different PhD projects. The “Environmental Impact Analysis”, which this thesis is part of, resulted in four of the appended publications (**Papers I-IV**). **Papers III** and **IV** was a result of multidisciplinary research, between PhD students and supervisors of the three different subprojects.

The last paper (**Paper V**) belongs to the “Sustainable Drivetrains” project funded by KTH-Sustainability and was performed by researchers at the Division of Environmental Strategies Research (fms) and the Department of Machine Design at KTH, with valuable input from researchers of the Integrated Transport Research Lab (ITRL) at KTH.

Abstract

In response to global environmental concerns and in particular resource depletion and climate change, vehicle manufactures have adopted different strategies for improving the environmental performance of their fleet and reduce the high energy demands and carbon dioxide (CO₂) emissions during the operation phase. Reducing the weight of the vehicle is among the most common ones. New lighter materials such as composites are introduced that facilitate weight reduction without compromising functionality, comfort and safety. In addition to that, alternative propulsion systems are available, with electric vehicles constantly increasing their share in the market. Despite the considerable benefits in relation to the operation phase of the vehicle, both design strategies have been associated with increased environmental impact during the manufacturing phase and also recyclability limitations at the end of life (EOL) stages. In order to address and increase understanding on these trade-offs a more holistic and life cycle approach is necessary when vehicle design strategies are developed and assessed.

This thesis explores up to what extent such a life cycle approach is adopted in vehicle design today. The aim of this work is twofold: 1) to increase understanding on the ways that vehicle design strategies for reducing fuel consumption, have been and can be assessed from an environmental and life cycle perspective, and 2) to contribute to method development for improved life cycle environmental performance of vehicles. This research has been focusing on lightweight design and electric drivetrains as two of the major design strategies adopted today, by assessing and discussing their potential to improve the life cycle environmental performance of vehicles.

In order to explore and increase understanding on current practices an empirical study was performed. Data for the study was collected through interviews with four vehicle manufacturing industries in Sweden. The results indicated that although the studied companies are aware of the major environmental challenges in relation to their products and work intensively to fulfil the increasing regulatory and customer requirements, environmental considerations during product development processes and material selection in particular, often lack a holistic lifecycle perspective. In relation to the use of tools for assessing and integrating environmental aspects into product development (namely Design for Environment (DfE) tools), variations among the companies were observed while only a limited number of such tools were utilized in a systematic manner and mainly for monitoring compliance purposes. This thesis showed, however, that a rich and diverse toolbox is available and different tools or combinations of tools can be considered suitable to be used during vehicle design and development stages. Most of the tools listed in this work, cover aspects that were identified as important from a vehicle design perspective, such as relevant environmental impacts, life cycle considerations, customer requirements and more.

The influence of new design strategies on the life cycle environmental performance of vehicles was assessed in three case studies; two of them looking into lightweight design and applying quantitative life cycle assessment (LCA) and one looking at alternative drivetrains and electric vehicles based on a streamlined LCA approach. Both strategies were shown to offer energy and greenhouse gas (GHG) emissions savings, although the impact during manufacturing increases due to more advanced and energy demanding materials. The actual level of this trade-off however, depends on the underlying assumptions relating to the operational life of the vehicle, fuel efficiency or, for the case of electric vehicles, the carbon intensity of the energy supply mix.

Despite its low share in terms of environmental impact, EOL has an important role in the overall environmental performance of vehicles which is expected to increase in the future.

The thesis contributed to method development by suggesting a systematic and life cycle approach for material selection. The suggested approach combines traditional material analysis to environmental assessment tools and consists of five steps: (1) Definition of design target, (2) Selection of material families and candidate materials, (3) Weight minimization, (4) Life cycle modelling and assessment, and (5) Results analysis and Material selection.

The thesis concludes that with systematic processes, integrated tools and metrics that manage to capture relevant environmental challenges for this product category, possibilities for life cycle improvements are increased, minimizing the risk for omissions and sub-optimizations.

Keywords: Vehicle design; Design strategies; Lightweight design, Electric vehicles; Design for Environment (DfE); DfE tools; Life cycle assessment (LCA); Simplified LCA; Composite materials

Sammanfattning (Summary in Swedish)

Som ett svar på de globala miljöutmaningarna och i synnerhet resursutarmning och klimatförändringar, har fordonsindustrin utvecklat olika designstrategier för att förbättra miljöprestandan hos sin fordonsflotta och minska de höga energikraven och koldioxidutsläppen (CO₂) under användningsfasen. Att minska fordonets vikt är bland de vanligaste designstrategierna. Nya lättare material som kompositer har utvecklats, som underlättar viktminskning utan att kompromissa med funktionalitet, komfort och säkerhet. Dessutom utvecklas alternativa framdrivningssystem, där elfordon ständigt ökar sin andel på marknaden.

Trots de betydande fördelarna under användningsfasen av fordonet, kan båda dessa designstrategier kopplas till ökad miljöpåverkan under tillverkningsfasen och även till återvinningsbegränsningar i livscykeln slutskede. För att åtgärda och öka förståelsen för dessa avvägningar är ett mer holistiskt och livscykelbaserat perspektiv nödvändigt när fordonsdesignstrategier utvecklas och utvärderas.

Denna avhandling undersöker i vilken mån ett sådant livscykeltänkande används inom fordonskonstruktion idag. Syftet är dubbelt: 1) att öka förståelsen för hur fordonsdesignstrategier som syftar till att minska bränsleförbrukningen har och kan bedömas ur ett miljö- respektive livscykelperspektiv, och 2) att bidra till metodutveckling för bättre livscykelmiljöprestanda hos fordon. Denna forskning fokuserar på lättviktskonstruktion och elektriska drivsystem som två av de stora designstrategierna idag, genom att bedöma och diskutera deras potential att förbättra miljöprestandan under hela fordonslivscykeln.

För att undersöka och öka förståelsen för nuvarande praxis har en empirisk studie genomförts. Data för studien samlades in genom intervjuer med fyra fordonstillverkningsindustrier i Sverige. Resultaten av studien visade att även om de studerade företagen är medvetna om de stora miljöutmaningarna som är kopplade till deras produkter och trots att de arbetar intensivt för att uppfylla ökande reglerings- och kundkrav, saknar ofta produktutvecklingsprocesser och i synnerhet materialvalet ett helhetslivscykelperspektiv. När det gäller användningen av verktyg för att bedöma och integrera miljöaspekter i produktutvecklingsprocesser (nämligen, produktutvecklingsverktyg för miljön), observerades stora variationer mellan företagen. Endast ett begränsat antal sådana verktyg användes på ett systematiskt sätt och framför allt för kontroll och uppföljning av regelverk. Denna avhandling visar att en rik och varierad verktygslåda är tillgänglig och att olika verktyg eller kombinationer av verktyg kan anses lämpliga att användas under fordonsdesign och olika fordonsutvecklingsstadier. De flesta av de verktyg som behandlas i detta arbete täcker aspekter som har identifierats som viktiga ur ett fordonsdesignperspektiv, som t.ex. relevant miljöpåverkan, livscykelöverväganden, kundkrav med mera.

Inverkan av nya designstrategier på livscykelmiljöprestandan hos fordon har utvärderats i tre fallstudier. Två av dem bedömer lättviktsdesign med hjälp av kvantitativ livscykelanalys, och en fokuserar på alternativa drivlinor och elfordon som bedöms på ett kvalitativt sätt. Båda designstrategier visade sig ge energi- och växthusgasutsläppsbesparingar även om påverkan under tillverkningsfasen ökar särskilt på grund av de mer avancerade och energikravande materialen. Nivån på denna avvägning beror på antaganden avseende fordonets operativa livslängd, bränsleeffektivitet, eller i fallet elfordon, koldioxidintensiteten i energiförsörjningsmixen. Trots sin låga andel när det gäller miljöpåverkan har slutskedet en viktig roll i den övergripande miljöprestandan hos fordon och den förväntas öka i framtiden.

Slutligen bidrar denna avhandling till metodutveckling genom att föreslå ett systematiskt och livscykelbaserat perspektiv vad gäller materialval. Den föreslagna metoden kombinerar material- och miljö analysverktyg och består av fem steg: (1) Definition av designmål, (2) Val av materialfamiljer och kandidatmaterial, (3) Viktminimering, (4) Livscykelmodellering och livscykelbedömning, och (5) Resultatanalys och Materialval.

Avhandlingen drar slutsatsen att med systematiska processer, integrerade verktyg och mått som klarar av att fånga relevanta miljöutmaningar, ökar möjligheterna till livscykel förbättringar medan risken för brister och suboptimeringar minskar.

Nyckelord: Fordonskonstruktion; Designstrategier; Lättviktsdesign, Elektriska fordon; Miljövänlig produktutveckling; Produktutvecklingsverktyg för miljön; Livscykelanalys (LCA); Förenklad LCA; Kompositmaterial

Acknowledgements

I am sincerely thankful to all the people who, in different ways and during different phases of this *journey*, supported me and contributed to this work.

I would like to thank the Centre for ECO² Vehicle Design at KTH for funding this PhD project and for providing a multidisciplinary research environment. Thank you all friends and colleagues of the center for the interesting discussions during ECO² seminars, courses and other joint activities. I would also like to thank KTH Sustainability and the Division of Environmental Strategies Research (fms) for also funding different parts and activities related to this work.

I am extremely grateful to my supervisor Anna Björklund for her guidance and continuous support from the beginning until the end of my studies. Anna, I really appreciate your trust and valuable help, when needed the most. I would also like to express my gratitude to my co-supervisor Per Wennhage for always being supportive and encouraging. I am thankful to my former supervisor Sara Tyskeng for giving me the opportunity to become a doctoral student and for our short, yet fruitful cooperation.

I am very thankful to Pontus Cerin, who was the KTH internal quality reviewer and Göran Finnveden, who was the internal reviewer at the Division of Environmental Strategies Research (fms), for their detailed and valuable feedback on my cover essay.

I would like to thank all co-authors of my papers, Anna Björklund, Christof Schneider, Conrad Luttrupp, Dan Zenkert, Katja Tasala Gradin, Lars Jerpdal, Malin Åkermo, Per Wennhage, Sara Tyskeng and Sohrab Kazemahvazi, for their valuable contribution and for sharing their ideas. I really enjoyed working with you all and I certainly gained a lot from our discussions and cooperation.

All employees at the four companies, who participated to the interviews, are gratefully acknowledged for their time and contribution to the study. I would like to thank Peter Georén for his valuable input to the Sustainable Drivetrains project and all the people who assisted in data collection for the different papers of this work.

A big thank you goes to all my colleagues and friends at the Division of Environmental Strategies Research (fms) for providing such an inspiring and friendly working environment, but also for all beautiful moments we spent together. I really missed the time being with you all during the last months of my studies. Sofii, Yevgeniya, Luciane and Jacob, thank you for your great company and for helping me in different ways during all this time.

Special thanks to all my friends here in Sweden, in Greece but also in other parts of the world for their understanding, encouragement but most important for sharing so many beautiful moments together. No matter the distance you are all in my mind and heart!

I am very grateful to my beloved family for their encouragement, infinite love and support. I would like to thank my parents in law Χρήστος and Ελένη and my brother and sister in law Αλέξανδρος and Βιολέτα for being supportive and understanding and for making me part of their family. Γιαγιά Βιολέτα, thank you for your love and for being so caring. Θεοδωρή, Αντιγόνη, Βέτα, Κώστα, Θέμη, Ιωάννα, Λυδία...thank you always being by my side. Θείο Γιώργο and θεία Γεωργία, thank you for your support and for making me feel like *home*.

To my beloved grandparents, παππού Γιάννη and γιαγιά Σοφία, I own my deepest appreciation and love. I know that those who are no longer with us, Κοσμάς and Δέσποινα are feeling the same happy and proud. I would also like to express my deepest gratitude and appreciation to my dear parents Γιώργος and Αναστασία and my sister Δέσποινα. Thank you for your infinite love and support in my life. Without you none of these would have been possible.

Ένα πολύ μεγάλο ευχαριστώ στην οικογένειά μου για την αμέριστη στήριξη και βοήθεια που μου προσέφερε όλα αυτά τα χρόνια! Σας ευχαριστώ μέσα από την καρδιά μου για την αγάπη σας, την υπομονή σας και που είστε πάντα δίπλα μου!

Last but not least, I am enormously thankful to my husband Dimitris and my son Christos. Dimitri and Christo this effort is dedicated to you. Dimitri, you have been an inspiration to me. Thank you being so patient and helpful. Thank you for your love and care and for your endless support and encouraging words during my studies. My sweet baby Christos, thank you for coming to our life and for making every day meaningful and unique. Your smile is my motivation. I love you both so much!

Thank you all!

Sofia Poulikidou

Helsingborg, September 10th 2016

List of appended papers

Paper I: Poulidikou S., Björklund A., Tyskeng S. (2014) Empirical study on integration of environmental aspects into product development: processes, requirements and the use of tools in vehicle manufacturing companies in Sweden. *Journal of Cleaner Production*, (81), pp 34-45 <http://dx.doi.org/10.1016/j.jclepro.2014.06.001>

Paper II: Poulidikou S. Overview and classification of Design for Environment tools – A diverse toolbox for vehicle developers (Submitted Manuscript)

Paper III: Poulidikou S., Jerpdal L., Björklund A., Åkermo M. (2016) Environmental performance of self-reinforced composites in automotive applications - Case study on a heavy truck component. *Journal of Materials and Design*, 103, pp 321-329 <http://dx.doi.org/10.1016/j.matdes.2016.04.090>

Paper IV: Poulidikou S., Schneider C., Björklund A., Kazemahvazi S., Wennhage P., Zenkert D. (2015) Material selection approach to evaluate material substitution for minimizing the life cycle environmental impact of vehicles. *Journal of Materials and Design*, (83), pp 704-712 <http://dx.doi.org/10.1016/j.matdes.2015.06.079>

Paper V: Tasala Gradin K., Poulidikou S., Björklund A., Luttropp C. Comparative streamlined LCA of Internal Combustion and Electric drivetrains (Submitted Manuscript)

Contribution to the co-authored papers:

All co-authored papers appended to this thesis were planned and outlined by the authors involved. Sofia Poulidikou was responsible for writing the main parts of **Papers I, III and IV**. In **Paper I** Sofia Poulidikou collected and analyzed the data while the co-authors and supervisors assisted in framing and revising the paper. In **Paper III** the LCA model was developed by Sofia Poulidikou with guidance from her supervisor Anna Björklund. Data were collected by Sofia Poulidikou and Lars Jerpdal. Lars Jerpdal assisted also in writing parts of **Paper III**. All co-authors assisted in revising the paper. In **Paper IV**, the LCA model was developed by Sofia Poulidikou with guidance from her supervisor Anna Björklund. Data were collected by Sofia Poulidikou and Christof Schneider. Christof Schneider was responsible for the weight optimization part with guidance from Dan Zenkert, Sohrab Kazemahvazi and Per Wennhage. All co-authors assisted in revising the paper. **Paper V** was written by Katja Tasala Gradin and Sofia Poulidikou. Katja Tasala Gradin collected the core data and modelled the streamlined LCA. Sofia Poulidikou assisted in data analysis. All co-authors assisted in outlining and revising the paper.

Other publications by the author:

Laurenti R., Lazarevic D., Poulidou S., Montrucchio V., Bistagnino L., Frostell B. (2014) Group Model-Building to identify potential sources of environmental impacts outside the scope of LCA studies, *Journal of Cleaner Production*, (72), pp 96-109 doi: 10.1016/j.jclepro.2014.03.001

Poulidou S., Björklund A. (2013) Tools for sustainable product development: Experience and requirements from the vehicle manufacturing industry in Sweden. Paper presented at the Life cycle management Conference-LCM 2013, Gothenburg Sweden, August 2013

Poulidou S., Tyskeng S., Björklund A., Wennhage P. (2012) Integration of environmental aspects in product design and development: an interview study of vehicle manufacturers in Sweden. Paper presented at the 19th International Product Development Management Conference Manchester UK, June 2012

Laurenti R., Lazarevic D., Poulidou S., Montrucchio V., Frostell B., Bistagnino L., Wennersten R. (2012) Using causal maps to identify potential sources of environmental impact outside the scope of LCA studies: preliminary findings from case studies on washing machines and road vehicles. Paper presented at the 18th Annual International Sustainable Development Research Conference Hull UK, June 2012

Licentiate thesis:

Poulidou S. (2013) Integration of Design for Environment in the vehicle manufacturing industry in Sweden: Focus on practices and tools. Licentiate thesis, KTH Royal Institute of Technology, Stockholm Sweden

Report:

Poulidou S. (2012) Literature review - Methods and tools for environmentally friendly product design and development. Identification of their relevance to the vehicle design context Report ISSN1652-5442, TRITA-INFRA-FMS 2012:2, KTH Royal Institute of Technology, Stockholm Sweden

List of Abbreviations

ARIZ	Algorithm for Inventive Problem Solving (from Russian acronym)
BEV	Battery Electric Vehicle
C/VE	Carbon fiber Vinyl-Ester
CAD	Computer Aided Design
CAFE	Corporate Average Fuel Economy
CBR	Case Base Reasoning
CE	Concurrent Engineering
CED	Cumulative Energy Demand
CF	Carbon Fiber
CFRC	Carbon Fiber Reinforced Composite
CO ₂	Carbon Dioxide
CO ₂ eq.	Carbon Dioxide Equivalent
CSA	Canadian Standards Association
CSPD	Checklist for Sustainable Product Development
DfE	Design for Environment
DfR	Design for Recycling
DfX	Design for X
E2PA	Environmental Efficiency Potential Assessment
EDST	Environmental Design Support Tool
EEA	European Environmental Protection Agency
EEA	Environmental Effect Analysis
E-FMEA	Environmental Failure Mode Effect Analysis
E-LCC	Environmental Life Cycle Cost (analysis)
ELCD	European Life Cycle Database
ELV	End of Life Vehicle
EOL	End of Life
EQFD	Environmental Quality Function Deployment
ERA	Environmental Risk Assessment
ERPA	Environmental Responsible Product Assessment
EU	European Union
EV	Electric Vehicle
FCV	Fuel Cell Vehicle
FRC	Fiber Reinforced Composite
G/VE	Glass fiber Vinyl-Ester
GADSL	Global Automotive Declarable Substance List
GF	Glass Fiber
GFRC	Glass Fiber Reinforced Composite
GHG	Greenhouse Gas
GWP	Global Warming Potential
HEV	Hybrid Electric Vehicle
HoE	House of Ecology
ICE	Internal Combustion Engine
ICEV	Internal Combustion Engine Vehicle
IEA	International Energy Agency
ILCD	International Reference Life Cycle Data System
IMDS	International Material Database System

IMRR	Impact of Modules on Recyclability Rate
IPCC	Intergovernmental Panel for Climate Change
ISO	International Organization for Standardization
km	Kilometer
LCA	Life Cycle Assessment
LCDSM	Life Cycle Design Structure Matrix
LCE	Life Cycle Engineering
LCM	Life Cycle Management
LC-QFD	Life Cycle Quality Function Deployment
Li-ion	Lithium Ion
MCA	Multi-Criteria Analysis
MECO	Materials Energy Chemicals Other
MET	Materials Energy Toxicity
MIPS	Material Intensity Per Unit Service
MJ	Mega Joule
NHTSA	National Highway Traffic Safety Administration
NiMH	Nickel Metal Hydride
OECD	Organization for Economic Co-operation and Development
OPM	Oil Point Method
PC/PET	Polycarbonate/Poly (Ethylene Terephthalate)
PEFCRs	Product Environmental Footprint Category Rules
PET	Poly (Ethylene Terephthalate)
PHEV	Plug-in Hybrid Electric Vehicle
PSS	Product Service Systems
QFD	Quality Function Deployment
REACH	Registration, Evaluation, Authorization and Restriction of Chemicals
REE	Rare Earth Element
REEV	Range Extender Electric Vehicle
ReSICLED	Recovery Systems modelling & Indicators Calculation Leading to End-of-Life-conscious Design
ROHS	Restriction Of Hazardous Substances
SLCA	Streamlined Life Cycle Assessment
SMC	Sheet Molded Compounds
SrPC	Self-Reinforced Polymer Composite
SrPET	Self-Reinforced Poly (Ethylene Terephthalate)
TRIZ	Theory of Inventive Problem Solving (Russian Acronym)

Table of Contents

Preface.....	iii
Abstract.....	v
Sammanfattning (Summary in Swedish)	vii
Acknowledgements.....	ix
List of appended papers.....	xi
List of Abbreviations.....	xii
1. Introduction.....	1
1.1 Background.....	1
1.2 Aim and scope of the thesis.....	2
1.3 Structure of the thesis and contribution of the appended papers	3
1.4 Outline of the cover essay	4
2. Theoretical context.....	5
2.1 Industry and the environment.....	5
2.2 The life cycle of products – Calls for a broader perspective	6
2.3 Product development.....	7
2.4 Material selection	8
2.5 Design for Environment (DfE) – Definition and key elements	9
2.6 Adoption of the DfE approach in industry.....	11
2.7 The use and diffusion of DfE tools – Requirements for successful integration	12
3. Vehicle design strategies for improved environmental performance.....	14
3.1 Lightweight design.....	14
3.1.1 Lightweight materials in vehicles	14
3.1.2 Polymer composites – potentials and limitations	15
3.1.3 Self-reinforced composite polymers (SrPCs)	16
3.1.4 Lightweight (sandwich) structures.....	16
3.2 Alternative propulsion systems; the case of electric vehicles.....	16
4. Methodology.....	19
4.1 Case study.....	20
4.2 Literature review.....	21
4.3 Qualitative research interviews.....	22
4.4 Environmental assessment.....	24
4.4.1 Life cycle assessment (LCA).....	24
4.4.2 Environmentally Responsible Product Assessment (ERPA).....	26
4.5 Weight optimization.....	27
5. Summary of results and discussion	28
5.1 Mapping current practices and available tools	28
5.1.1 Exploring current practices on DfE implementation and utilization of DfE tools....	28
5.1.2 Availability of tools in literature.....	32

5.2	Assessing vehicle design strategies from a life cycle perspective	37
5.3	Contribution to method development	42
5.4	Contributions and limitations of the thesis	44
6.	Conclusions and recommendations for future work.....	47
6.1	Recommendations for future work.....	48
	References.....	50
	Appendix: Interviews protocol used for Paper I.....	59

List of Figures

Figure 1	Contribution of the appened papers to the objectives of this thesis	4
Figure 2	Product development as part of the company’s business environment and structure; Redrawn from (Johannesson et al., 2013)	7
Figure 3	Key stages of the product design and development process (Pahl et al., 2007; Ulrich & Eppinger, 2008)	8
Figure 4	A generic material selection process (Ashby, 2011).....	9
Figure 5	Influence of life cycle driving distance on CED and GWP for a diesel truck (Paper IV). Note: The values in the vertical axis of the CED figure should have been $\times 10$ instead of $\times 10^4$	42
Figure 6	Framework for life-cycle based materials selection as developed and presented in Paper IV. The dashed lines show processes that are outside the scope of the suggested approach but could be included in the model.	43

List of Tables

Table 1	List and characteristics of electric drivetrain alternatives	17
Table 2	Overview of the research strategy and methods used in the appened papers of this thesis.....	20
Table 3	List of features that are used for the analysis of the identified DfE tools (Adapted from Paper II).....	22
Table 4	Sample specifications (Adapted from Paper I)	23
Table 5	Summary of results on DfE implementation and utilization of tools (adapted from Paper I).....	29
Table 6	List of tools mentioned by the interviewees from the four companies studied (Paper I)	30
Table 7	Analysis of the identified DfE tools based on the selected features.....	35

1. Introduction

1.1 Background

As the need to address the climate and energy challenge becomes urgent, transport is a key sector where action is required. Recent figures show that the transport sector is responsible for about a third of the final energy demand and about a quarter of greenhouse gas (GHG) emissions in Europe (European Commission, 2013) as well as worldwide (IEA, 2015). More than 80% of these figures is accounted to road transports (passenger cars, light and heavy duty trucks) that to a large extent continue to rely on fossil based fuels such as gasoline and diesel for their operation (European Commission, 2013).

The pressure towards improved environmental performance of vehicles has increased as a result of regulation and customer requirements. Noteworthy example is the new target on carbon dioxide (CO₂) emissions from passenger cars introduced by the European Union (EU) (Regulation (EC) No 443/2009, 2009), which sets the fleet average to be achieved by all new cars developed from 2021, to 95 grams of CO₂ per kilometer (km); lowered by 27% compared to the 2015 levels. Similar restrictions have been introduced in the United States under the Corporate Average Fuel Economy (CAFE) standard (93 g/km by 2025) as well as China (117 g/km by 2020) and Japan (105 g/km by 2020) (ICCT, 2014; NHTSA, 2009).

In response to the increased requirements, automotive manufacturers work intensively on strategies that would improve the environmental performance of their fleet. Over the last decade the emissions of CO₂ per km from petrol and diesel passenger cars in Europe have been reduced in average by 27% and 21% respectively (EEA, 2015). This progress has been a result of not only engine performance improvements and increased drivetrain efficiency but also due to innovations in vehicle design (such as lighter vehicles) that assisted in reducing the fuel consumption during the operation stage of vehicles (Kim et al., 2010). In addition to that, the road vehicle fleet has been enriched with cleaner technologies and alternative fuel or propulsion systems; biofuels such as ethanol and electric vehicles (EV) are some examples (Moriarty & Honnery, 2008).

Fuel consumption of vehicles is determined by many different factors, weight being one of them. A 10% reduction in weight is estimated to save up to 8% of fuel depending on the driving cycle, type of the vehicle and other operating conditions (Cheah, 2010; Wohlecker et al., 2007). For this reason, lightweight design is a common design strategy among vehicle manufacturers (Kim et al., 2010). Lightweight design can be realized through material substitution or by the development of more material efficient structures. New lighter materials are introduced that facilitate weight reduction without compromising functionality, comfort and most important safety. For passenger car manufacturers the incentives for lightweight design are high. Truck or rail vehicles are considerably heavier although weight reduction in these sectors is also relevant not only in terms of energy efficiency improvements but also for the possibilities of increased payload. From a societal point of view increased payload provides opportunities for more efficient and sustainable transports of people and goods.

A technological advancement in vehicle development is the introduction of alternative propulsion systems such as fuel cell vehicles (FCV), battery electric vehicles (BEV) and hybrid electric vehicles (HEV) with the latter ones constantly increasing their share in the global market (OECD-IEA, 2016). Although the fleet of BEV and HEV remains small, these alternative drivetrains have the potential to lead to significant energy and emission reductions (Stephan & Sullivan, 2008).

From the aforementioned examples, it becomes apparent that the major focus on innovation and design strategies of the transport sector has been in improving the performance of the vehicle during the operation phase (Samaras & Meisterling, 2008). That can be expected considering the long lifetime and high energy demands of vehicles during that stage which determine their life cycle environmental performance. The more recent studies, however, have started to draw a different picture.

Using lightweight materials such as composites and high performance metals result in considerable energy savings during the operation phase of the vehicle. These lightweight materials however, have an energy intense manufacturing phase which may offset the potential savings when the complete life cycle of the vehicle is considered (Duflou et al., 2012; Kim et al., 2010; Lewis et al., 2014; Witik et al., 2011). In addition, composite materials introduce new challenges at the end of life (EOL) stage since recycling and recovery possibilities of these materials are low (Witik et al., 2011). The life cycle environmental performance of internal combustion engine vehicles (ICEVs) and electric vehicles (EVs) has been investigated by Hawkins et al. (2013). The finding of their study reported an increase of the environmental impact during the manufacturing stage of the EV as a result of batteries production. Similar results have been presented by Faria et al. (2013) and Ma et al. (2012).

Conclusions from these studies indicate that a more holistic and life cycle approach is needed when vehicle design strategies are developed and assessed. Taking into consideration the improvements during the use phase a shift towards other life cycle stages is expected that need to be sufficiently explored. The extent to which such a holistic approach is already adopted in automotive industry is one of the topics discussed in this thesis. Although the vehicle manufacturing is one of the leading sectors with a long tradition on eco-design strategies, there is still room for improvements as it will be shown in later chapters. Additionally, this thesis contributes to life cycle thinking implementation with a material selection approach that combines traditional material analysis tools to environmental assessment tools. The aim and research questions posed in this work are described in more details below.

1.2 Aim and scope of the thesis

The aim of this thesis is to increase understanding on the ways that vehicle design strategies aiming at reducing fuel consumption, have been and can be assessed from an environmental and life cycle perspective but also to contribute to the development of a systematic approach for material selection. This research focuses on lightweight design and electric drivetrains as two of the major design strategies adopted today, by assessing and discussing their potential to improve the life cycle environmental performance of vehicles.

To fulfil the aforementioned aim, three main objectives were formulated, each one addressing specific research questions (RQ):

A. To map and increase understanding on the current practices and available tools

RQ 1: What environmental aspects are prioritized by the Swedish vehicle manufacturing industry and what tools and processes are currently adopted for identification and evaluation of design strategies?

RQ2: What tools are available that can assist the systematic identification and assessment of design strategies for improved environmental performance of vehicles?

B. To assess vehicle design strategies from a life cycle perspective

RQ3: How do new design strategies for reducing fuel consumption affect the life cycle environmental performance of vehicles and what key factors should be in focus when new design strategies are assessed?

C. To contribute to method development for improved life cycle environmental performance of vehicles

RQ4: How can environmental assessment tools be integrated during product design and material selection processes?

A “design strategy” is defined as the plan of action to gain competitive advantage, aiming to merge and bring together the business strategy and goals, to the product design and development processes (Olson et al., 1998). In this thesis, I refer to design strategies as the design alternatives that have been adopted in order to reach a specific goal (for example reducing the energy use during the operation phase of the vehicle).

1.3 Structure of the thesis and contribution of the appended papers

This thesis consists of an introductory part (cover essay) and five appended papers. Each paper contributes to one or several of the research questions posed in Section 1.2 while collectively they have been performed to contribute to the aim of the thesis. Figure 1 illustrates the contribution of the appended papers to the three objectives of this thesis.

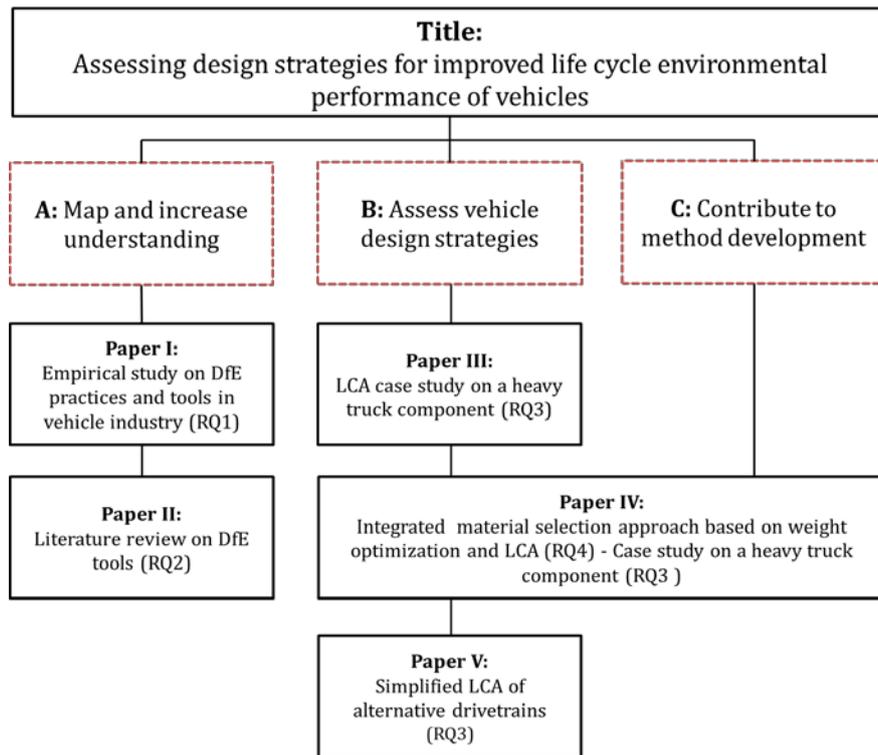


Figure 1 Contribution of the appened papers to the objectives of this thesis

The study presented in **Paper I** provides empirical data on the integration of environmental requirements during vehicle design and development processes and assists in answering **RQ1**. **Paper II** answers **RQ2** by investigating the availability of tools for assessing and integrating environmental aspects into product design and development processes. The aim of **Paper II** was to map the research area and provide vehicle developers a useful toolbox. **Papers III, IV** and **V** answer **RQ3**. **Papers III** and **IV** present a comparative life cycle assessment (LCA) of different material alternatives for lightweight design while in **Paper V** two drivetrain technologies are assessed in a qualitative manner. **Paper IV** contributes also to method development and answers **RQ4** by introducing and testing an integrated material selection approach.

1.4 Outline of the cover essay

Chapter 1 provided a brief introduction to this thesis along with the aim and key research questions addressed. Chapter 2 and Chapter 3 aim to provide the necessary background on the different concepts discussed in the thesis and appended papers. More specifically, Chapter 2 focuses on the process of product development and the integration of environmental considerations and tools during that process while Chapter 3 discusses vehicle design strategies and developments that are of relevance to this work. The research strategy of this thesis together with the methods used in the different papers, are described in Chapter 4. Chapter 5 summarizes and discusses the findings of the appended papers based on the thesis objectives and research questions. The contributions and limitations of this thesis are briefly discussed in the same chapter. Finally, the conclusions of this work are presented in Chapter 6 where recommendations for future research are also provided.

2. Theoretical context

This chapter provides the theoretical context and background of this thesis and principally the work presented in **Papers I, II and IV**. Among others product development, material selection, life cycle thinking, Design for Environment (DfE) and DfE tools are briefly described below representing key elements and concepts related to this work.

2.1 Industry and the environment

In order to meet the growing demands for products and services, humans have caused significant changes to the ecosystem and natural environment through for instance the massive exploitation of resources and increased emissions of pollutants and waste. Industry is most often seen as part of the problem i.e. as a major contributor as regards today's environmental challenges. It would be wise however, to consider industry as part of the solution as well, since it has also succeeded in providing innovative technologies and environmentally improved products and services that may assist the transition towards sustainable development.

The view of companies towards global environmental challenges and their responsibility in improving their own environmental performance has changed and significantly improved over the years; sometimes through voluntary initiatives, although most of the times as response to environmental regulation and customers' pressure (Porter & van der Linde, 1995). Over time improving the environmental performance and profile of the organization has become a strategic element. Companies realized that there are many associated benefits such as competitive advantage, reduced cost through resource efficiency, good image etc. (ibid). In order to develop and remain competitive however, companies need to be proactive and able to adapt when new environmental challenges emerge.

A holistic view on industrial activities may assist in identifying the sources of environmental impacts but also possibilities for improvement. Companies are an interactive part of the society and the natural environment where they operate. A broad network of actors and processes form the business environment of the company. To illustrate the range of actions taking place in the company and the continuous interactions (inputs and outputs) with its internal and external environment Holmberg (1998) assigns four roles to a company; the role of purchaser of resources and services, the role of resource converter, the role of supplier of products or services as well as the role of communicator and information exchanger. Through these different roles, companies have a great opportunity to influence and minimize the negative effect of their activities on the natural environment by, among others, using materials and resources efficiently, adopting cleaner manufacturing processes and providing environmentally superior products, technologies or services.

Taking the right measures for improved environmental performance requires information in relation to the different environmental constraints associated to the company's activities and products. Thus, processes that would provide such information at different levels of the company and in a good time are necessary. Although a clear boundary between the environmental performance of the product and the in-house environmental performance of the

organization is often difficult to set, the focus of this thesis is on strategies and measures that aim to improve the environmental performance of the product as the main goal and outcome of the industrial activities.

2.2 The life cycle of products – Calls for a broader perspective

Products are often conceived as artefacts that have been developed to fulfil a predefined function. After a shorter or longer period of time and when they are no longer in use, most products end up as waste. The concept of “life cycle of products” expands this linear picture to illustrate production, use and disposal as continuous, circular and interconnected activities. When the environmental performance of a product is concerned all these stages have their own contribution to it. Some products have a material and resource intense manufacturing stage while for others the major environmental burden is associated to their operational life.

Although environmental impacts occur in different stages over the life cycle of the product, the majority of them have been determined earlier. The environmental performance of the product is defined to a great extent at the same time as the product is developed; when decisions about materials, manufacturing processes, functions, life span or performance are decided. It has been noted by numerous authors that product design and development is a strategic phase for the “environmental adaptation” of products (Hallstedt et al., 2013; Ritzén, 2000).

Such a broader perspective in relation to the life cycle of products has already been incorporated in various initiatives as well as regulation measures and environmental management schemes. One example is the Integrated Product Policy (IPP) introduced by the European Commission (COM (2001) 68, 2001) that points towards the direction of more systematic and integrated product development practices where the life cycle impacts of the product are considered by all stakeholders involved. The Eco-design directive (Directive 2009/125/EC, 2009) emphasizes the responsibility of the manufacturer and introduces a set of guidelines aiming to improve the life cycle environmental performance of energy consuming products.

Moreover, the REACH, Registration, Evaluation, Authorization and Restriction of Chemicals regulation (Regulation (EC) No 1907/2006, 2006) and ROHS, Restriction of Hazardous Substances directive (Directive 2002/95/EC, 2002) are associated with the material composition of products aiming to minimize the use of toxic and potentially harmful substances. Waste prevention policies and the product specific End of Life Vehicles (ELV) directive (Directive 2000/53/EC, 2000) aim to address explicitly the EOL stage by suggesting measures and setting specific recyclability targets.

Finally, the revised and recently published environmental management standard ISO 14001:2015 has made the need for companies to integrate environmental considerations into their product planning and developing processes more apparent. The standard has evolved from previous versions to promote life cycle thinking and places special focus on the environmental performance of the product (Ciravegna Martins da Fonseca, 2015; Lewandowska & Matuszak-Flejszman, 2014).

The aforementioned developments have already started to change the ways product development processes are organized as well as the priorities set. It becomes clear that in order

to comply with these regulations, all different phases of the life cycle of the product should be improved from materials and manufacturing processes to EOL treatment possibilities.

2.3 Product development

Product development is a process that aims to transform an idea or market opportunity into a technical and commercial solution (Whitney, 1990). It describes both the development of new products as well as modifications of existing ones. Product development is a strategic process for the organization. As a highly interactive process, it involves different actors operating within the system boundaries of the company; for example customers, regulators and competitors as shown in Figure 2. All of these actors set requirements and demands that need to be integrated and balanced to the company’s own visions and goals.

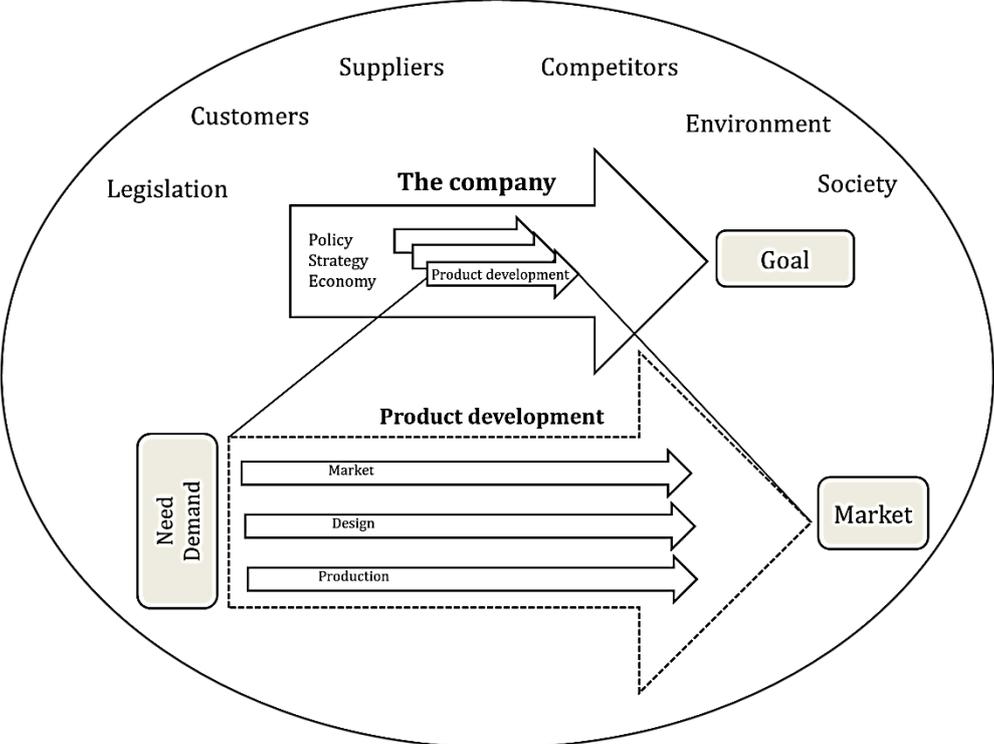


Figure 2 Product development as part of the company’s business environment and structure; Redrawn from (Johannesson et al., 2013)

Generic models illustrating the product development process and major activities involved exist in the literature. Key stages of the product development process, as shown in Figure 3, include: product planning, conceptual design, embodiment or detailed design, product review and final production (Pahl et al., 2007; Ulrich & Eppinger, 2008). Although organizations tend to customize their product development process based on their own needs, resources and routines these generic models can be considered quite representative.

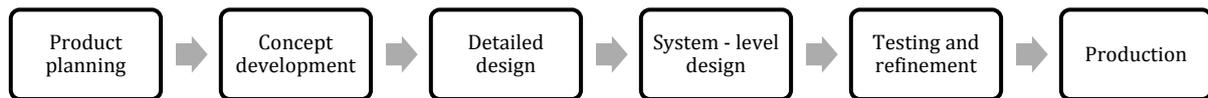


Figure 3 Key stages of the product design and development process (Pahl et al., 2007; Ulrich & Eppinger, 2008)

Product planning (also referred to as problem identification) is the first step of the product development process where the needs of the market and business opportunities are identified and ideas for potential products are created (Pahl et al., 2007). This step involves participants and receives input from different parts of the organization (such as marketing, research and development, sales etc.) as well as from external actors e.g. customers, suppliers or regulators (Johannesson et al., 2013). The result of this step is a list of technical specifications and requirements. During the consecutive stage of concept planning and design, different product concepts or design alternatives are developed aiming to fulfil the requirements defined before. Among the different concepts and alternatives, one is selected to be further developed and designed (principle alternative) at the embodiment and detailed design stages (Pahl et al., 2007). Moving towards the last pre-manufacturing stages details of the product are determined including shape, materials, production processes etc. Refinements and revisions may be necessary before the final launch, thus product development is an iterative process (ibid).

Typically, two different types of product development processes can be identified; technology driven and product driven. The former aims to technology development and to apply technologies that are not currently on the market. The latter based on market demands and competing products applies existing technologies and refers to more incremental modifications (Tingström, 2007). In both cases, product development is a highly structured process aiming to increase time efficiency from idea creation to the market. For this reason and to deal with the increased number of information and input to the process, product development has evolved from linear to more integrated processes with parallel working groups, increased information exchanges and use of various supporting tools (Lindahl, 2005). These are often called concurrent engineering (CE) or life cycle engineering (LCE) models (Hallstedt, 2008; Tingström, 2007).

Such integrated and formalized models for product development are identified to be followed by the companies participating to the studies of this thesis as shown in **Paper I**, where product planning and design are key activities for determining the requirements and attributes of future products or technologies.

2.4 Material selection

Material selection is part of the product development process and an activity of high importance. The overall performance and actual design of the product is influenced by the choice of materials. Material selection may take place in early design and development stages where different material options are evaluated for new applications but also in projects where new materials are investigated to substitute existing ones. Material selection itself may also be

performed in stepwise procedures like the one illustrated in Figure 4. It is often considered as a complex activity where a multiple of requirements and constraints need to be considered and fulfilled. The overall objective is to match the functional and performance requirements of the intended application with the properties of the respective materials (mechanical, physical etc.). However, thousands of materials are available today and selecting the most appropriate one is often a puzzle for product designers.

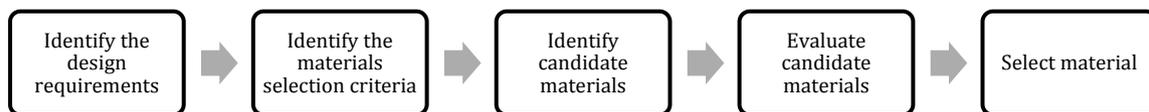


Figure 4 A generic material selection process (Ashby, 2011)

The functional and performance requirements (indicated as “design requirements” in Figure 4) are defined by the respective application or product. In turn material selection criteria are defined based on four major areas: (1) material properties, (2) material cost and availability, (3) material processing and product manufacturing, (4) environmental performance (Ashby, 2009). The materials that fulfil performance, design and cost requirements can be considered as candidate materials for the product or application. Until recently these were the major aspects considered during material selection. The increased pressure for low environmental footprint has added the environmental performance as a new parameter in the material selection process. In the material selection model presented by Ashby (2009), environmental information is provided, together with the physical and mechanical properties of the material, in the form of environmental footprint indicators for instance energy or CO₂ footprints. Detailed models on material selection where physical characteristics are combined with environmental performance indicators have been developed by for example Ermolaeva et al. (2004), Giudice et al. (2005) and more.

2.5 Design for Environment (DfE) – Definition and key elements

Given the rising environmental challenges and the potential of product development to minimize those challenges, the role of engineer designers and product developers has changed. New products are expected to be functional and appealing and have a low environmental footprint. In order to be able to deal with this challenge systematic and integrated product development processes are needed that consider environmental together with functional and economic attributes. Such integrated processes are referred to as “Design for Environment” (DfE) or “Ecodesign” practices.

Fiksel (2011) defines DfE as “the systematic consideration of design performance with respect to environmental health, and safety objectives over the full product and process life cycle” while Ecodesign refers to the “integration of environmental aspects into product design and development, with the aim of reducing adverse environmental impacts throughout a product's life cycle” (ISO 14006, 2011). The two terms are very similar and often used interchangeably. In

this thesis the term Design for Environment (DfE) is adopted and used to describe the systematic integration of environmental aspects and requirements during product design and development processes. DfE aims to address and minimize the environmental impacts of a product throughout its life cycle without compromising other criteria like quality, function, cost etc. (ISO TR/14062, 2002).

A broad list of publications is available on how DfE can be implemented in practice while a big variety of frameworks and tools have been developed to enable such integration (Brones & Monteiro de Carvalho, 2015). According to the literature three key elements of the DfE approach can be identified and are addressed in this thesis: (1) early consideration of environmental aspects into product development, (2) life cycle thinking and (3) use and integration of supporting DfE tools.

Early consideration of environmental aspects into product development

According to Bhamra (2004), the “early stages” of product development refer to the activities that take place before the detailed design specification phase of the product. Incorporating the environmental performance of the product during those early stages is considered the most efficient way to minimize the negative impact of products on the environment (Bhamra, 2004; Ritzén, 2000). Not only because most of environmental aspects are determined during design decisions, but also due to the high degree of design freedom at those early stages (Luttrupp & Lagerstedt, 2006). At later design stages and as specifications of the product are decided, opportunities for modifications are fewer and in most cases more expensive to perform.

Life cycle thinking

DfE encourages designers and all actors involved in the product development 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); from the extraction of raw materials or natural resources, to the manufacturing, use, recycling and final disposal (ISO TR/14062, 2002). Life cycle thinking assists in obtaining a holistic picture of the product and the system in which it is embedded. Hence, it offers higher possibilities for identification and minimization of trade-off situations, i.e. 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 cycle thinking provided the foundations for a variety of frameworks and methodologies such as Life Cycle Assessment (LCA), Life Cycle Management, (LCM), the Integrated Product Policy (IPP), Design for Environment (DfE), and more.

Use and integration of supporting DfE tools

The third key element of the DfE approach is the use of DfE tools (Johansson, 2002; Lindahl, 2005; Tingström, 2007). The term “tool” in this context is defined in a broad sense as any type of systematized aid to incorporate environmental aspects into the product design and development process (Baumann et al., 2002). The overall goal of such tools is to provide methodological support and guide product development towards the most relevant improvement strategies (Byggeth & Hochschorner, 2006; Hallstedt, 2008). DfE tools may also facilitate communication and information exchanges within the product development process (Lindahl, 2006). 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 but also to

generate or compare improvement strategies (Baumann et al., 2002; Byggeth & Hochschorner, 2006; Poulidikou, 2012). 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 (Poulidikou, 2012). Numerous reviews of DfE tools are available that may assist practitioners to the identification and selection of suitable tools. Among the most recent ones are the literature reviews performed by Bovea and Perez-Belis (2012), Birch et al. (2012), Pigosso et al. (2015) and Rossi et al. (2016).

While initially considered a prescriptive tool or complication of design guidelines, the notion of DfE and DfE implementation has expanded to a product development management approach involving and affecting different levels and actors of the organization (Boks & McAloone, 2009; Johansson et al., 2007). According to Tingström (2007) implementation of DfE strategies require management commitment, structured processes, DfE mind-set and use and adoption of DfE tools. Similarly Hallstedt et al. (2013) devised a list of 8 key elements for integrating sustainability strategies into product development and innovation, classified in four main areas; organization, processes, roles and tools. The work presented in this thesis does not investigate all of these elements to the same extent. The focus has been on the DfE mind-set (in a broader sense of acquiring relevant information) and DfE tools. Issues relating to the ways that DfE processes are structured and the people involved are touched upon in **Paper I**. The thesis however, does not go into details regarding the effectiveness or management implications of these processes.

2.6 Adoption of the DfE approach in industry

The adoption of the DfE principles and approach in industry has been explored in numerous publications (Bey et al., 2013; Deutz et al., 2013; Handfield et al., 2001; Jönbrink et al., 2013; Kara et al., 2014; Lindahl, 2006; Short et al., 2012). Companies have been working on providing environmentally improved products and services in different ways and to different extents (Kara et al., 2014). Demands from regulation and customers, expected competitive advantage or economic advantage, environmental policy of the company or individual interest are among the most commonly reported drivers for adoption of the DfE strategies in industry (Bey et al., 2013; Kara et al., 2014; Short et al., 2012).

Boks and McAloone (2009) report a transition in relation to DfE practices being introduced in specific projects that focused mostly on environmental aspects and “low-hanging fruits” to more systematic and integrated processes today. Similarly, Johansson et al. (2007) describe the development and implementation of DfE practices in industry to evolve from the “start-up” phase, to the “consolidation” phase and now being in the “modern business-integrated” phase.

Although these findings demonstrate a positive progress, there are still barriers to overcome. Results from empirical studies show that companies are still facing difficulties to prioritize and implement DfE practices during product design and development (Deutz et al., 2013; Handfield et al., 2001; Jönbrink et al., 2013; Short et al., 2012; Tukker et al., 2001). Handfield et al. (2001) and Tukker et al. (2001) were among the first to demonstrate the maturity gap between theory and practice when it comes to DfE implementation. This gap remains evident in the more recent

studies of Deutz et al. (2013) and Jönbrink et al. (2013). Their findings not only indicate variations in environmental awareness among different companies but integrating environmental aspects into design processes seem to be “far from standard practice” as they conclude. Companies continue to work on “single issues” e.g. energy efficiency improvements, or restrictions of certain materials and chemicals that hinders the proactive and holistic adoption of DfE principles and allows only for incremental environmental improvements (Jönbrink et al., 2013; Thompson et al., 2011).

Dekoninck et al. (2016) classify the barriers for DfE implementation in five major areas: strategy, tools, collaboration, management and knowledge. More specifically lack of management commitment, support and motivation, lack of resources, time and cost constrains, organizational complexities, lack of routines, lack of information and expertise, unwillingness to cooperate and communication gaps between proponents and executors of DfE strategies are among the most commonly reported (Bey et al., 2013; Boks, 2006; Jönbrink et al., 2013). All these however, are proven to have a significant influence and being determining factors for the successful implementation of the DfE approach and strategies.

2.7 The use and diffusion of DfE tools – Requirements for successful integration

A similar gap and lack of integration is reported for the case of DfE tools. Despite the apparent maturity and constant development of DfE tools in literature, there is limited evidence of their use in practice (Baumann et al., 2002; Lindahl, 2005; O'Hare et al., 2010; Rossi et al., 2016). Only a few studies demonstrate systematic utilization of DfE tools while LCA is among the tools most often applied (Kara et al., 2014; Thompson et al., 2011; Tingström et al., 2006). The majority of publications report utilization of DfE tools in pilot projects (Bovea & Perez-Belis, 2012) while other aim to compare DfE tools based on empirical case studies and participatory action research (Knight & Jenkins, 2009; Tingström & Karlsson, 2006; Vallet et al., 2013).

Different reasons that hinder the diffusion of DfE tools have been reported in literature. For example: no demand for tools in the product development process, tools complexity and need for environmental expertise, limited time to learn and use the tool in an efficient manner, data constraints (especially for advanced analytical tools), lack of integration to the design process and tools that engineer designers are using (Lindahl, 2006; Lofthouse, 2006; Millet et al., 2007; Rossi et al., 2016). Another limitation relates to the actual lack of knowledge on the available tools. It is often the case 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 a result, companies may have been using tools that are not suitable for them or may not using tools at all.

Selection and customization of DfE tools are essential activities in order for these tools to be successfully integrated into the design process (Ernzer & Birkhofer, 2002; Knight & Jenkins, 2009; Ritzen & Lindahl, 2001). Product developers are encouraged to obtain information on a broad range of tools and be confident to choose the ones that are most relevant and suitable for them (Bhander et al., 2003). In general DfE tools should be able to:

- capture environmental challenges that are of relevance to the company and product (Ernzer & Birkhofer, 2002)
- provide a holistic life cycle perspective in order to avoid sub-optimizations and shifts of environmental impacts (Byggeth & Hochschorner, 2006)
- support decision making (Byggeth & Hochschorner, 2006) and
- provide knowledge and enhance communication and cooperation among the people involved in the product development process (Tingström & Karlsson, 2006)

Moreover, DfE practitioners and designers often express the need for DfE tools to be easy to understand and implement i.e. having low education and deployment requirements. These aspects however, depend a lot on the resources and experience of the company. It can be concluded that the product per se, the structure of the company and product development process as well as the expertise available are very likely to determine the selection of the right DfE tools.

3. Vehicle design strategies for improved environmental performance

Vehicles have long life cycles and belong to the broad category of “active products” indicating that energy is needed for their operation (Johannesson et al., 2013; Lindahl, 2000). Usually the environmental impact of such products is determined by the use phase and vehicles are no exception at least up until now. As a result and in order to reduce the energy consumption during the use phase of vehicles, the major strategies adopted by the automotive industry include improving engine efficiency, reducing the weight of vehicles and introducing alternative, less carbon intense fuels and propulsion systems. The strategies considered and discussed in more detail in this thesis concern lightweight design and alternative propulsion systems (passenger EVs). Key elements in relation to these strategies are shortly described in Sections 3.1 and 3.2 providing the background material for **Papers III, IV and V**.

3.1 Lightweight design

Lightweight design is a material selection and product development process aiming to reduce the weight of a product or component. The same steps and constraints discussed in Section 2.4 are applied while all together they shall provide a design with the lowest possible weight.

Lightweight design can be realized in different ways including material substitution and by designing more material efficient structures. Material substitution, i.e. replacing heavier materials in different parts of the vehicle with lighter ones, is the main strategy for lightweight design that is discussed in this thesis. In addition, a short reference to the concept of sandwich structures is made as a means to obtain material efficient designs. Material substitution was applied in **Papers III and IV** while the concept of sandwich structures was used to design the component studied in **Paper IV**.

3.1.1 Lightweight materials in vehicles

Two decades ago, ferrous metals like cast iron and steel comprised more than 60% of the material composition of an average passenger car (Sullivan et al., 1998). As the demands for lighter vehicles emerge, new materials were developed and introduced aiming to reduce the overall weight of a vehicle. Among others the use of high performance steel, magnesium or aluminium alloys started to increase as a means to replace heavier steel grades and iron components. Although metals continue to dominate in today’s road and rail vehicles their average composition has changed significantly especially when passenger cars are concerned. A characteristic example is the increased use of polymers. The share of polymers in different parts of a passenger car has reached more than 15% of the weight depending on the vehicle (Lyu & Choi, 2015). Due to inferior properties in comparison to metals however, the application of polymers has been mainly to interior parts or components with lower stiffness and strength requirements. However, the development of advanced engineering materials such as polymer composites managed to provide alternatives even for load carrying and more demanding automotive applications.

3.1.2 Polymer composites – potentials and limitations

Composites are materials that are made from two or more constituents, the reinforcement and the matrix material. The reinforcement carries the mechanical loads, defining the strength of the final material while the matrix is protecting the reinforcement by absorbing and distributing the loads (Åström, 1997). The main feature of composite materials is that the final material exhibits considerably improved properties (such as stiffness, strength, or environmental resistance) compared to the constituent materials individually. Increased specific stiffness in practice means less material to fulfil a function and for this reason composites are very attractive material alternatives for lightweight designs.

Different types of composite materials exist. In automotive applications fiber reinforced composites (FRC) are most commonly used for body panels and other parts of the vehicle. These can be made for example from carbon or glass fibers (used as reinforcement) and a polymer based resin (used as matrix). Glass fiber reinforced composites (GFRCs) such as sheet molded compounds (SMC) are among the most commonly found composite materials in automotive applications. Despite being stronger, carbon fiber reinforced composites (CFRCs) are more expensive and therefore their introduction to vehicle components has been slower (Asensi, 2016).

The polymer resins used in composite materials can be divided into two groups namely thermoset and thermoplastic resins (Ashby, 2009). The major difference is that thermoset resins (like polyester) require chemical crosslinking; an irreversible process where the resin reacts chemically with the reinforcement and therefore it cannot be separated and reshaped. In contrast, thermoplastic resins can be melted, separated and reshaped again (ibid).

A variety of manufacturing methods for composite materials and components exist, of different levels of automated work procedures or manual work requirements. The selection of the most appropriate one is determined by the type of polymer resin used for the composite (thermoplastic or thermoset), the shape and size of the component as well as cost (Åström, 1997). For composite materials it is often the case that raw material and final component are made during the same manufacturing process. Alternatively, raw materials can be supplied in different pre-impregnated forms. For the types of composites that are used in automotive industry, compression molding techniques are the most common to manufacture SMC components that are based on a thermoset resin (unsaturated polyester) while resin transfer molding (such as injection molding) is a preferable alternative with thermoplastic resins (Åström, 1997).

The development of advanced composite materials is expected to increase their use also for structural vehicle applications. From a mechanical and lightweight design point of view such materials is a very promising technology. The vehicle manufacturing industry however, would have to face the challenge of energy intense manufacturing processes and limited recyclability potential. The argumentation around the former is that the higher energy demands of production are compensated by the lower energy requirements for operation during the life cycle of the vehicle. The latter however, is more difficult to overcome as the European Directive has already since 2015, set a minimum of 95% reuse and recovery target for ELVs (Directive 2000/53/EC, 2000). At the moment recycling incentives of composites materials are low due to market and cost constraints. Moreover, incineration for energy recovery can also be problematic

due to their low heating value (Hedlund-Åström, 2005). The majority of composite materials are disposed in landfills something that contradicts with the waste prevention policies posed by EU (e.g. (Directive 2008/98/EC, 2008)) and result in considerable loss of resources.

3.1.3 Self-reinforced composite polymers (SrPCs)

A new group of composite materials has been developed having the potential to provide a recyclable alternative. These composites are called self-reinforced composite polymers (SrPCs) or single-polymer composites (Alcock & Peijs, 2013). A key characteristic of these materials is that the matrix and reinforcement are made by the same (currently polymer based) material (Kmetty et al., 2010). Examples of common thermoplastic polymers that are used in SrPCs include Polypropylene (PP), Polyethylene (PE), or poly (ethylene terephthalate) (PET).

Previous studies have shown that Self-reinforced poly (ethylene terephthalate) (SrPET) can be an attractive material for automotive applications due to the inherent properties which makes it comparable with GFRCs that are currently in use (Jerpdal & Åkermo, 2014; Schneider et al., 2013). From an environmental perspective SrPET and SrPCs in general can be a preferable choice due to higher recycling potentials compared to common thermoset composite materials. Being new, the potential of these materials needs to be further investigated before they can be more widely introduced in practice. **Papers III** and **IV** appended in this thesis provide such initial investigations that may facilitate development and adoption of these new materials.

3.1.4 Lightweight (sandwich) structures

An alternative way to reduce weight is by the use of material efficient structures such as sandwich structures. A sandwich structure consists of three elements: the two faces (two outer layers) and the center core (Åström, 1997). Sandwich structures may provide good mechanical properties without increasing the weight of the structure. As layers, high performance materials are often used such as polymer composites or sheet metals. The core is usually a lower performing material. Wood, polymer foams or corrugated structures are often used as core materials. Manufacturing processes applied to sandwich structures are similar to those of composite materials (Åström, 1997).

Due to the heterogeneity that some sandwich structures exhibit (as they often consist of three or more different materials) similar separation and recyclability limitations can be encountered as for the case of composite materials. The possibilities to use SrPCs in lightweight sandwich structures have been explored in previous research (Schneider, 2015) and in **Paper IV** with the aim to provide material efficient and recyclable alternatives for automotive applications.

3.2 Alternative propulsion systems; the case of electric vehicles

Electric propulsion systems exist for more than 100 years (OECD/IEA, 2013). The technology has been adopted mainly in rail vehicles and less in passenger cars or trucks where the internal combustion engine (ICE) dominated. Despite being considerably more energy efficient, EVs were not capable of reaching the travel range freedom offered by ICEVs due to the low energy density of their batteries. Development and improvements of the electric propulsion systems along with the need for less polluting vehicles have facilitated the reintroduction of EVs in the market.

During the last decade a considerable increase of EVs sales has been reported. In 2014, the global EV registrations almost tripled compared to the 2012 levels (OECD/IEA 2016).

Different electric drivetrain combinations are available i.e. hybrid electric vehicles (HEVs), plug in hybrid EVs (PHEVs) or range-extended electric vehicles (REEVs), battery electric vehicle (BEVs) and hydrogen fuel cell vehicles (HFCVs) (Ma et al., 2012; Tate et al., 2008). The majority of EVs (except HFCVs) use batteries to store energy while their difference lies in the ways that power is supplied and stored in the batteries. Key characteristics of the different electric drivetrain alternatives are provided in Table 1.

Table 1 List and characteristics of electric drivetrain alternatives

Type	Drivetrain/s	Function
HEVs	Internal combustion engine and electric drivetrain	The vehicle can use both systems. Energy to the electric drivetrain is supplied from the ICE or through regenerative braking (i.e. HEVs do not use electricity).
PHEVs	Internal combustion engine and electric drivetrain	The vehicle can use both systems. Electricity to the electric motor is supplied from external sources in charging stations. Additional power can be provided by the ICE.
REEVs	Electric drivetrain, equipped with an internal combustion engine	Electricity to the electric motor is supplied from external sources in charging stations. The ICE is not providing power to the wheels directly, but to the batteries.
BEV	Electric drivetrain	Electricity to the electric motor is supplied from external sources in charging stations. Additional energy can be supplied through regenerative braking.
HFCV	Electric drivetrain	Electricity to the electric motor is provided by the fuel cells in the vehicle using compressed hydrogen and oxygen from the air.

When compared to ICEVs the main difference of EVs stands in the drivetrain (i.e. the electric motor, batteries and power electronics) (Elwert et al., 2016). The remaining parts of the EVs such as the car body, chassis, and interior parts remain essentially the same while similar materials can be expected (Hawkins et al., 2013). EVs are usually heavier than ICEVs, due to the heavier battery pack that requires also more space in the vehicle.

The battery is a key component of EVs because it determines its range and travel capabilities when used in electric mode. Nickel metal hydride (NiMH) and Lithium-ion (Li-ion) are two major batteries technologies used in EVs today, with the latter constantly increasing their share (Elwert et al., 2016; Majeau-Bettez et al., 2011). Research and development on EV batteries has been focusing on increasing their energy density and life span but also in reducing recharging time. All these parameters are expected to influence and determine the performance comparison between EVs and ICEVs thus the future of the adoption and share of EVs in the market.

The electric drivetrain is more complex than the conventional internal combustion engine in terms of parts and equipment, requiring also more advanced materials (Cullbrand & Magnusson, 2011; Elwert et al., 2016). Examples include rare earth elements (REE) such as neodymium and dysprosium that are found in the permanent magnet motors as well as lithium, cobalt, and copper (Elwert et al., 2016). The use of copper for instance is more than two times higher in EVs compared to a conventional but still highly equipped vehicle while similar variations are observed for neodymium and cobalt (Cullbrand & Magnusson, 2011).

Due to availability constraints, supply monopoly as well as high environmental impact, materials such as REE or cobalt are labelled as critical materials while the use of lithium should also be closely monitored (Elwert et al., 2016; European Commission, 2014; Tukker, 2014). The dependence of EVs on these materials entails risks for the automotive industry not only in terms of supply shortage and higher prices but also in terms of increased environmental impact as shown in recent studies (Ma et al., 2012; Messagie et al., 2014).

Additional concerns arise in relation to the EOL stage of EVs. As a new technology, only a limited volume of EVs can be expected to have reached the ELV stream today. Thus recovery and recycling of EVs and EVs components have not been established on a large scale yet. For the case of traction batteries, EU poses a minimum of 50% recycling efficiency target by average weight (Directive 2006/66/EC, 2006). Due to the inherent differences between EVs and ICEVs however (in terms of drivetrain design and materials) the preparedness of the current recycling systems to manage and recover materials from these drivetrains, is rather uncertain (Elwert et al., 2016). Valuable materials can then be lost to construction materials, backfilling materials and landfills (Andersson et al., in press).

While environmental comparisons between EVs and ICEVs focus on the use phase performance and the potential of EVs to reduce GHG emissions, the differences in terms of materials and the associated challenges discussed above seem to be receiving less attention in publications related to EVs (Hawkins et al., 2012; Nordelöf et al., 2014).

4. Methodology

This chapter describes the research strategy of this thesis and the methods applied in the appended papers. Depending on the research questions raised throughout this work different qualitative and quantitative approaches were utilized that assisted in defining the context of the study and study objects, in data collection and in data analysis. An overview of the research strategy is provided in Table 2 linking the appended papers to the respective methods applied. The reader may also refer back to Figure 1 for information on how the papers link to the aim and objectives of the thesis.

The first research question (**RQ1**) was addressed through an explorative, empirical study (as described in **Paper I**) aiming to investigate the current DfE practices and use of DfE tools in the Swedish vehicle manufacturing industry. Case study research assisted in defining the study objects. Data were collected through semi-structured interviews and then analyzed based on the transcribed material and thematic areas obtained.

In order to answer **RQ2**, on the available tools for identifying and assessing design strategies, a literature review study was designed as described in **Paper II** and further in the text.

RQ3 was answered through a combination of studies (**Papers III, IV and V**). The environmental performance of new materials and drivetrain technologies was assessed in three different environmental assessment case studies where different environmental impact analysis tools were applied, namely LCA and the Environmental Responsible Product Assessment method (ERPA).

Paper IV addresses also **RQ4**, by developing a new approach for material selection where LCA was an integrated part of the decision making process. The approach was tested with the use of a case study. The novelty of the study is that weight optimization models are utilized as a primary source of information for product specification since the suggested approach is expected to take place before the final product is available.

Table 2 Overview of the research strategy and methods used in the appended papers of this thesis. Methods and abbreviations are further explained in the text.

Appended Papers	Research strategy and methods
<p>Paper I (RQ1) : Empirical study on integration of environmental aspects into product development: processes, requirements and the use of tools in vehicle manufacturing companies in Sweden</p>	<p>Defining context/application area: Case study Data collection: Qualitative research interviews Data analysis: Word to word transcription, division in thematic areas, comparisons to literature</p>
<p>Paper II (RQ2): Overview and classification of Design for Environment tools –a diverse toolbox for vehicle developers.</p>	<p>Defining context/application area: Case study Data collection: Literature review Data analysis: Classification- list of properties obtained from literature review and Paper I</p>
<p>Paper III (RQ3): Environmental performance of self-reinforced composites in automotive applications - Case study on a heavy truck component</p>	<p>Defining context/application area: Case study Data collection: Questionnaires, databases, literature review Data analysis: LCA (using GWP and CED)</p>
<p>Paper IV (RQ3 & RQ4) : Material selection approach to evaluate material substitution for minimizing the life cycle environmental impact of vehicles</p>	<p>Defining context/application area: Case study Data collection: Questionnaires, databases, weight optimization model, literature review Data analysis: LCA (using GWP and CED)</p>
<p>Paper V (RQ3) : Comparative streamlined LCA of Internal Combustion and Electric drivetrains</p>	<p>Defining context/application area: Case study Data collection: Personal communication, literature review Data analysis: ERPA (using predefined impact categories)</p>

4.1 Case study

A case study is defined as “an empirical inquiry of a contemporary phenomenon within its real-world context” (Yin, 2009). A key feature of case study research is the interest in deriving an in depth understating of a single or a small number of cases (Yin, 2012). Case study research can be used to answer explanatory or descriptive research questions and is broadly applied in different scientific fields from natural sciences to medicine or social sciences. Depending on the aim and objectives of the study, a variety of qualitative and quantitative tools can be used in order to obtain results.

The research performed in this thesis focuses on the vehicle manufacturing sector and vehicle design. All five appended papers have vehicle design as a starting point and apply case study research to different extent, for different purposes and by using different methods and tools to obtain results. **Paper I** applies case study research in order to obtain empirical data on the environmental aspects that are prioritized today in the vehicle industry and the tools used. The

Swedish vehicle manufacturing industry, consisting of four large international companies, was investigated (multiple case studies). The selection of these companies offered the opportunity to cover different modes of transport and thus provide examples of road as well as rail vehicles design. The variety and diversity of cases was of greater interest than quantity (of similar cases). For this reason the scope was not expanded to include more industries of the same sector located in other regions.

In **Paper II** case study research can be considered an auxiliary method assisting in framing the aim of the paper and providing the context for the selection of analysis properties of the identified tools. Although the main aim of the paper was to provide vehicle developers with a rich and diverse toolbox, the applicability of the identified tools during vehicle design was not further tested on empirical case studies.

In **Papers III-V** environmental assessment tools were applied in different case studies in order to assess different material or drivetrain alternatives from an environmental and life cycle perspective. The use of case studies in these specific papers assisted in increase understating on the environmental performance of the different alternatives but also in illustrating the trade-offs that may be encountered when new design strategies for reducing fuel consumption are considered. Moreover, in **Paper IV** the case study was used in order to apply and illustrate the integrated material selection approach that was suggested in the paper and therefore assist the reader and potential user to increase understanding on the steps involved. The case study also assisted in finding the strengths and limitations of the suggested approach.

4.2 Literature review

Literature based research methodology (usually referred to as simply literature review) describes the systematic process of collecting, analyzing and evaluating scholarly material (Fink, 2010). In **Paper II**, literature review served as a stand-alone qualitative research method. The key steps followed in the study were:

- determination of research question and relevant sample (e.g. databases, journals etc.)
- determination of searching parameters
- searching and data collection
- screening and evaluation
- classification and analysis
- presentation of results

The core aim of the paper was to compile an inventory on DfE methods and tools and highlight aspects of the tools that can be relevant in a vehicle design context. Databases of scientific journals (such as Scopus) and the catalogue of the KTH Library in Stockholm were screened in order to find information in peer reviewed articles, conference proceedings or academic publications and books. In addition, reports and webpages of commercially available tools were investigated. The keywords searched included: eco-design/eco-design tools, design for environment/design for environment tools, environmental impact assessment/environmental impact assessment tools, life cycle assessment. No year limitation was applied. Both publications that described a specific tool or reviews of tools were considered as relevant.

Due to the large number of publications obtained, a screening process was applied in order to select tools for further analysis. Thus, the review included only:

- tools for which sufficient information could be acquired
- tools relating to the environmental performance of products and not the performance of manufacturing facilities or the performance of a company in general
- from a sustainability perspective, the focus of the review has been on tools that focus on the ecologic and economic performance of the product, i.e. tools investigating social sustainability were not included

Moreover, procedural tools and standards, i.e. tools supporting companies in the procedures of integrating environmental aspects into product development, were not included. The main reason was that procedural tools typically rely on results from analytical tools as for instance the framework developed by Simon et al. (2000), or target different levels and actors in the organization (not only the product development process) as the (ISO 14006, 2011).

The DfE tools were classified into three groups based on the support that they can provide to the product development process; prescriptive, analytical and tools that aim to identify design strategies (also referred to as eco-ideation tools). The identified tools were analyzed based on product specific requirements obtained from the literature and from an earlier empirical study performed by the author (**Paper I**). The aim was to highlight features of the tools that would be more relevant from a vehicle design perspective. The selected features are summarized in Table 3.

Table 3 List of features that are used for the analysis of the identified DfE tools (Adapted from Paper II)

Feature	Description
Input and output mechanisms	Type of data that is required and provided by the tool (Qualitative/quantitative/semi quantitative approach)
Systems perspective	Possibilities for relevant environmental aspects to be considered and assessed Possibilities to consider the life cycle of the product
Multi-criteria perspective	Possibilities to integrate functional requirements Possibilities to integrate customer requirements Possibilities to integrate regulation requirements Possibilities to integrate economic requirements Possibilities to identify trade-offs
Integration	Possibilities for integration with other tools (e.g. engineering design tools)

4.3 Qualitative research interviews

Research interviews are conversations that have a structure and a purpose (Kvale, 2009). According to Gillham (2005), interviews differ from other type of qualitative research methods such as questionnaires since (a) the questions asked during interviews are open i.e. the respondents provide their own answer; (b) there is a form of structure and a purpose from the side of the interviewer; and (c) there is an interactive relationship between the respondent and the interviewer that allows for adjustments or clarifications. Depending on the level of

interaction and adjustments, interviews can be classified as structured, semi-structured or open (Kvale, 2009).

Qualitative research interviews, was the primary method for data collection in **Paper I** following the procedure described by Kvale (2009). The aim of the paper was to collect primary data regarding the implementation of the DfE approach and the use of DfE tools in the four different companies studied. In total eighteen semi-structured interviews were performed. The target group in each company was personnel with environmental and DfE tools expertise as well as vehicle designers. Information on the profile of the respondents can be found in Table 4. More details on their expertise and working area can be found in **Paper I**.

Table 4 Sample specifications (Adapted from Paper I)

Company	Total number of respondents	Role of respondent in the company (No. of respondents)
A	5	Senior specialist for environmental features (1) Feature leader for materials and environment (1) Environmental engineer - consultants (2) Engineer designer (1)
B	4	Strategic advisor of environmental issues (1) Attribute leaders for environment (2) Engineer designer (1)
C	2	Senior engineer on vehicle verification and environmental regulation (1) Engineer designer - Group manager (1)
D	7	Manager for center of competence on Design for Environment (DfE) (1) DfE engineers in two different departments (5) Engineer designer (1)
Total:	18	Areas of expertise covered: Environmental managers, environmental experts, DfE tools experts and engineer designers

Questions posed during the interviews that relate to the research questions of this thesis included:

- questions relating to the processes of integrating environmental aspects and requirements during product development
- questions relating to the type of environmental objectives and requirements that are prioritized and integrated into their product development process, and
- questions relating to the DfE tools currently being used by the companies

A complete list of the major topics discussed can be found in the Appendix section of this thesis.

The majority of interviews were performed face to face and lasted for approximately one hour. Two telephone interviews were arranged as well due to distance constraints. The interviews were recorded and then transcribed. Respondents were given the opportunity to verify the content of the transcribed material and indicate possible confidential issues. Since no confidentiality limitations emerge, all material was used for further analysis using thematic clusters as suggested by Miles and Huberman (1994). The transcribed material was classified

under different clusters that were derived from the research questions as well as patterns observed in the text.

4.4 Environmental assessment

Among the aims of **Papers III-V** was to assess the environmental performance of different material alternatives as well as drivetrains from a life cycle perspective. The assessment was performed using LCA in **Papers III** and **IV** and the streamlined semi-quantitative approach ERPA in **Paper V**. The two methods are described separately below.

4.4.1 Life cycle assessment (LCA)

Life cycle assessment (LCA) is an analytical tool for evaluating the environmental performance of a product or service during its life cycle; i.e. from material extraction, to production, use phase and final disposal (ISO 14040, 2006). It accounts all inputs (in terms of raw materials, resources and energy) and outputs (emissions, by-products and waste) of a given system aiming to identify potential sources for environmental impacts. Based on established life cycle impact assessment methodologies the effect of these material, energy and emission exchanges from and to the natural environment can be estimated (Bauman & Tillman, 2004). The implementation process is supported by established standards and guidelines which increases the robustness and consistency in application of the tool. A milestone in LCA methodology was the development and introduction of the ISO 14040 standard series which provided a comprehensive framework around LCA methodology (ISO 14040, 2006; ISO 14044, 2006). In 2010 the International Reference Life Cycle Data System Handbook (ILCD) was developed (European Commission-Joint Research Centre-Institute for Environment and Sustainability, 2010) together with product specific guidelines (Product Environmental Footprint Category Rules (PEFCRs)). The Canadian Standards Association (CSA) has also published a LCA standard that applies specifically to passenger cars (SPE-14040-14, 2014).

LCA consists of four main steps in accordance to the ISO 14040 standard:

- a) Definition of the goal and scope of the study
- b) Inventory analysis
- c) Impact assessment
- d) Presentation and interpretation of the results

There are two methodological approaches in LCA namely the consequential and attributional approach (Finnveden et al., 2009). These two approaches vary in scope and have a significant influence on the data collection and modelling processes. The first approach also called change-oriented uses marginal data aiming to “describe how the environmental exchanges of the system can be expected to change as a result of actions taken in the system” (Rebitzer et al., 2004). The second approach (attributional or accounting) “describe a product system and its environmental exchanges” by using average data, and data that “reflect the actual physical flows to and from the studied system” (Finnveden et al., 2009).

Based on the purpose of the assessment two types of LCA studies can be distinguished; stand-alone or comparative (Bauman & Tillman, 2004). As LCA entails the collection and assessment of

a huge amount of data, software tools have been developed in order to enhance the implementation process of the method (Rossi et al., 2016). Examples include SimaPro (PRÉ Consultants, 2010), GaBi (thinkstep, 2015) and OpenLCA (OpenLCA, 2016) that are commercially available.

Results from LCA studies can be presented as raw data of inventory flows (such as material or energy flows). Impact assessment however, assists in linking the inventory data collected with potential environmental impacts thus providing a more comprehensive and meaningful outcome. A number of ready-made impact assessment methods exist and the selection of the most appropriate one depends on the data collected, the scope of the assessment and intended audience and more (Bauman & Tillman, 2004).

LCA was used in **Paper III** and **Paper IV**. A summary of the specifications and models applied are briefly presented below. More information can be found in the respective papers.

4.4.1.1 LCA specifications and models applied in Papers III and IV

Goal and scope definition

In **Papers III** and **IV** accounting comparative LCAs were performed. In **Paper III**, LCA was used as a tool to investigate the performance of the novel SrPET material and compare it with materials currently in use for the selected vehicle part (a truck panel). The functional unit of the case study was defined as: “two exterior panels for a heavy truck”. The panels were assumed to be used by a diesel truck weighing 40tn and covering a life time distance of 1,000,000 km. The three studied panels exhibit different properties e.g. material composition and weight in order to fulfil the functional specifications given by the manufacturer.

The system boundaries of the study included the stages of acquisition and production of the raw materials and panels, use phase of the panels as part of the vehicle and EOL of the panels. The transports occurring during the different steps were also considered. Identical processes such as distribution of the vehicle were excluded. Similarly processes that were expected to have a low influence of the outcome such as the process of assembling the part on the vehicle were also excluded.

In **Paper IV**, LCA was used as a tool to assess the environmental performance of six different material alternatives for a truck roof. The functional unit was defined as “one truck roof”. The design specifications for the roof were obtained from industry safety standards. The roof was used for a 40tn diesel truck while the lifetime distance covered was assumed to be 1,000,000 km. The system boundaries of the study included the stages of acquisition and production of the raw materials and roof, use phase of the roof, and EOL. As this was a theoretical case on a non-existing product, transports and assembly processes were not considered.

Allocation issues emerge in both studies. The most significant concerned the need to allocate the fuel consumption of the complete vehicle during the use phase to the specific component studied. For this purpose weight allocation was used in both papers assuming a linear correlation between weight and fuel consumption. Due to this simplification, sensitivity analyses were performed assessing alternative use phase scenarios. More information can be found in **Papers III** and **IV**.

Inventory analysis

In both papers the LCA software tool SimaPro 7 (PRé Consultants, 2010) was used as the core tool to model and perform the LCA study. For **Paper III**, primary data was used whenever possible while the rest of processes were modelled using generic data from Ecoinvent and the European Life Cycle Database (ELCD) available in SimaPro. In **Paper IV** the majority of data was based on literature and generic data from the Ecoinvent and ELCD databases.

Impact assessment

In both studies the life cycle environmental performance of the different material alternatives was assessed using the Cumulative Energy Demand (CED) (Huijbregts et al., 2010) and Global warming potential (GWP) (Frischknecht R. et al., 2007) indicators as applied in SimaPro. CED assesses all primary energy demands and is expressed in units of Mega joule (MJ). GWP evaluates the impact on climate. Using equivalency factors developed by the Intergovernmental Panel on Climate Change (IPCC) (IPCC, 2007), emissions of GHG are measured and displayed in terms of carbon dioxide equivalents (CO₂-eq).

Results interpretation

The life cycle results of the two studies were presented in different ways. First, a contribution analysis of the key life cycle stages was performed (manufacturing, use phase and EOL) followed by a separate contribution analysis of the manufacturing stage which was evaluated in more detail. Due to uncertainties in different stages of the life cycle of the components studied, a number of additional scenarios were developed and analyzed as sensitivity analyses. In **Paper III** sensitivity analyses were performed in relation to the SrPET concept design, the use phase conditions and EOL. In **Paper IV** variations in operating conditions, energy efficiency, and EOL were further assessed.

4.4.2 Environmentally Responsible Product Assessment (ERPA)

Environmentally Responsible Product Assessment (ERPA) is a semi-quantitative environmental assessment method developed by Thomas Graedel (Graedel, 1998). Semi-quantitative approaches although based on qualitative input data, may result in a quantitative outcome when scoring or valuation is applied. The method evaluates the environmental performance of the product under five impact categories; material choice, energy use, and solid-, liquid-, and gaseous residues and five life cycle stages; pre-manufacture/resource extraction, manufacture, delivery, use, and disposal. A 5X5 matrix is created where the rows indicate the environmental stressors and the columns the life cycle stages. The product is assessed by assigning a value from 0 to 4 to every cell of the matrix. The value 0 indicates the highest environmental impact (worst performance) while 4 indicates the lowest environmental impact (best performance). The rating is based on specific scoring guidelines provided by the method. The sum of the matrix element values defines the total environmental performance of the assessed product.

The ERPA method was used as the main evaluation tool for comparing the two prototype vehicles and drivetrains in **Paper V**. The prototype vehicles were identical in terms of structure and body, differing only in the drivetrain and batteries. That provided a unique opportunity to simplify the study and highlight the differences of the two prototypes that was the aim of the paper. Although quantitative data were not required to perform the study, there was still need

for quantitative information to be able to assess and rate the two drivetrains. Data were collected via personal communication with researchers at KTH, Stockholm and literature search. Moreover, the drivetrains were disassembled to provide primary information on the material composition of the two engines. The ERPA method does not require a strict definition of functional unit but to ensure that results were comparable the same function, i.e. equal lifetime and range, was assumed for both drivetrains.

The assessment and scoring process was based on the guidelines and scoring protocols provided by the manual of the method (Graedel, 1998).

4.5 Weight optimization

Paper IV investigated the possibilities to combine materials and environmental analysis tools in a systematic material selection approach. The goal of the suggested approach was to derive feasible and weight efficient design alternatives that were also assessed in terms of environmental performance with the help of LCA. The approach was tested on a case study of a truck roof as described earlier. When candidate materials for the roof were selected, the weight of the roof had to be determined. To derive the lowest optimal mass for the design alternatives, a weight optimization model was developed. Lowering the mass however, should not compromise functional requirements of the studied part. Therefore design constraints such as available space or maximum allowed deformation were defined and applied to the weight optimization model. The weight optimization function was generically defined as:

$$\text{Minimize } f_0(x_{(1:i)}) \quad (1)$$

$$\text{Subject to } f_k(x_{(1:i)}) \leq b_k, \quad k = 1 \dots n \quad (2)$$

$$\underline{x}_i \leq x_i \leq \bar{x}_i, \quad i = 1 \dots 5$$

Where, f_0 is the weight function which is a function of the design variables x_i . f_k is the constraint function while b_k represent the constraint values. \underline{x} and \bar{x} define the lower and upper boundaries for the design variables x_i which may represent the allowed wall thickness of the truck roof or other predefined constraints. The optimization model was designed and implemented in MATLAB®. More details on the model and background assumptions can be found in **Paper IV**.

5. Summary of results and discussion

This chapter presents and discusses key findings of the five papers appended to this thesis. The structure of the chapter follows the structure of the objectives and research questions listed in Section 1.2. The chapter ends with a reflection on the strengths and limitations of the thesis and the research strategy adopted (Section 5.4).

5.1 Mapping current practices and available tools

In order to explore and compare the theory and practice in relation to the ways that vehicle design strategies have been and can be assessed from an environmental and life cycle perspective, an empirical study and a literature review were performed. The results from these studies are presented and discussed in Sections 5.1.1 and 5.1.2 respectively.

5.1.1 Exploring current practices on DfE implementation and utilization of DfE tools

Current practices on DfE implementation were investigated in **Paper I** aiming to address **RQ1**: *“What environmental aspects are prioritized by the Swedish vehicle manufacturing industry and what tools and processes are currently adopted for identification and evaluation of design strategies?”*

Data for the study were collected through semi-structure interviews with employees at four major vehicle manufacturing companies in Sweden that produce road and rail vehicles as well as vehicle components. The diversity of end products covered (passenger cars, heavy duty vehicles, buses and trains), provided the opportunity to acquire a broad overview of the Swedish vehicle manufacturing sector. At the same time comparable results were obtained due to similarities in size, regulatory requirements and major areas of environmental concern. The sample of interviewees consisted of people that were directly or indirectly related to the product development process while the majority worked with aspects related to the environmental performance of the vehicle or vehicle components (see also Table 4, Section 4.3).

Paper I investigated the structure of the product development processes adopted by the four companies and the ways (in terms of activities, people and tools) that environmental aspects are integrated during these processes. Table 5 summarizes the findings of the paper.

Table 5 Summary of results on DfE implementation and utilization of tools (adapted from Paper I)

	Company A	Company B	Company C	Company D
Structured product development process	X	X	X	X
Structured DfE process	X	X	-	X
In-house environmental expertise	X	X	X	X
Environmental priorities and requirements	Production: Restricted materials and hazardous substances, emissions during manufacturing of vehicle; Operation: energy use, noise, air quality inside the vehicle; EOL: recyclability of materials and vehicle			
In-house DfE tools expertise	X	-*	-*	X
DfE tools				
Tools that generate strategies	X	X	X	X
Analytical tools	X	-	-	X
Monitoring tools	X	X	X	X

*Only the users of the monitoring tools (databases and substance lists)

Product development in all four companies is a structured and formalized process following the generic models described in earlier sections. For all studied companies improving the environmental performance of their products is among the core values thus environmental goals and requirements are set for all vehicles during early planning stages. Similarly to other sectors, regulation and customer demands determine these requirements to a great extent (Bey et al., 2013).

As shown in **Paper I** the studied companies have adopted different ways for identifying, assessing and integrating environmental considerations into their product development processes. In some cases a systematic DfE process was in place, with continuous involvement of environmental engineers and DfE experts throughout product development; from early planning to detailed design stages. For other companies, a more prescriptive model was adopted. Environmental requirements were defined and monitored centrally in the company with less interaction with the vehicle design departments and product development. Such variations led to different maturity levels in terms of DfE adoption and implementation between the companies, thus different strengths and limitations were identified.

Environmental priorities and requirements

In terms of environmental priorities, **Paper I** showed that vehicle manufacturers focus on similar aspects when it comes to improving the environmental performance of their products (as summarized in Table 5). Among the most important environmental constraints prioritized in product development include energy and resource consumption as well as GHG and other regulated emissions (especially during the operation stage). The design strategies mentioned in order to cope with these constraints were mainly related to performance and energy efficiency improvements, including lightweight design, alternative fuels and technologies.

Reducing the use of chemicals and potentially hazardous materials as well as aspects related to recycling and EOL of the vehicle were defined as another important area of concern among the companies. In terms of environmental performance, material alternatives are assessed with

respect to their impact on the weight of the vehicle and recyclability (by setting recycling targets). Material alternatives would also need to comply with different material and substance control standards introduced either as regulatory requirements or customer requirements and industry initiatives; for example the Global Automotive Declarable Substance List (GADSL) (American Chemistry Council Inc, 2010).

Utilization of DfE tools

The use of DfE tools is an area where greater variations among the studied companies were observed. The interviewees listed different types of tools that have been occasionally or more systematically used by the respective company (Table 6).

Table 6 List of tools mentioned by the interviewees from the four companies studied (Paper I). Shaded areas indicate that the tool was available and used in a systematic way. Non-shaded areas indicate that the tool was not available or the utilization level of the tool varied.

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

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.

The provided list covered a big range of tools; from prescriptive guidelines and monitoring tools to analytical ones, like LCA. DfE tools were used in different stages of the product development process and for different purposes; to collect information, to generate ideas, to assess different design alternatives or products, to monitor compliance and more.

Customer surveys, brainstorming processes and benchmarking indicators were among the tools mentioned by the interviewees for identifying design strategies and set environmental

requirements. Although these are not traditionally defined as DfE tools (or eco-ideation tools (Bocken et al., 2011)) they are commonly used in product development processes in order to generate new product ideas (Dominick et al., 2001). Environmental parameters however, are often added to the tools although no specific example was discussed with the interviewees. Two of the companies mentioned Environmental Failure Mode Effect Analysis (E-FMEA) or Environmental Effect Analysis (EEA) as customized tools that assisted in generating design strategies. No current use of these tools was, however, reported.

For assessing design strategies (including different technologies, components or material alternatives) analytical tools such as LCA were often used. LCAs were most commonly performed on finished products, although cases where new product concepts were assessed before the actual design stage were also reported. Not all companies used LCA to the same extent. Only two of the studied companies used LCA as a systematic method within the company and had a special software and LCA expertise in place. In the other two companies, LCA assessments were outsourced to academic researchers or consultants, since no tool or LCA expert was available in the company.

None of the respondents reported a systematic use of LCA in material selection processes but rather some individual studies that were performed when a need for such information was identified. Substance and chemical control lists, material databases as well as recyclability indicators were used to monitor and verify material compliance to different regulations and company targets. These tools are based on sector-specific initiatives and were adopted and customized by all four studied companies. Moreover, these were reported to be the most systematically applied tools during product design and development processes.

Additional ways to monitor the performance of different parts of the vehicle were mentioned by the respondents including simulations (e.g. on energy requirements) and other testing tools. Although these tools are also not defined as DfE tools, they can be considered very useful to the design groups and relevant from a DfE approach since they provide opportunities for tools integration (in conventional DfE tools) and the possibilities to obtain primary information on key environmental performance parameters.

Remarks and observations

Paper I indicates that the studied vehicle manufacturing companies adopt different ways for identifying and integrating environmental considerations into their product development processes. The findings of the study support the conclusion drawn from previous research that adoption of systematic processes for the environmental adaptation of products is still not a standard practice within industry (Dekoninck et al., 2016; Deutz et al., 2013; Jönbrink et al., 2013; Short et al., 2012). Key elements that may facilitate the DfE implementation process have been suggested in literature (Brones & Monteiro de Carvalho, 2015; Hallstedt et al., 2013; Johansson 2002; Tingström, 2007). Comparing these, to the findings of the study, missing elements were identified that may assist the studied companies in harmonizing and complementing existing processes or establishing new (discussed in **Paper I** in more detail). The discussion below focuses on the environmental requirements and DfE tools as two of these elements mostly related to the aim of this thesis.

The studied companies focus on relevant aspects aiming to improve the environmental performance of their product during the operation stage and meet the legal and customer

demands. This is the first step towards a successful adaptation of the environmental performance of the product (Johansson 2002). The DfE approach further suggests that design alternatives should be considered in a holistic and systematic way taking the life cycle implications into consideration (Fiksel, 2011; ISO 14006, 2011). Even for companies with in-house environmental expertise, environmental requirements remained narrow in scope, especially during material selection processes. Issues related to acquisition of raw materials, their production processes and the associated impacts were not always addressed. Technical aspects and cost were among the factors that determined material selection processes together with regulation compliance.

The most apparent gap with DfE literature, as indicated in **Paper I**, relates to the integration of DfE tools into the product development process and the effective use of information from these tools during design decisions. DfE tools may not only provide useful information to the product design process, but may also enhance communication among departments, and increase understanding and awareness on critical environmental constraints (Johansson et al., 2007; Lindahl, 2005; Tingström, 2007). The maturity in terms of experience and capabilities of the studied companies in relation to DfE tools however, varies considerably. As shown, not all companies use DfE tools to the same extent and especially environmental impact assessment tools. Two of the studied companies can be considered rather advanced in terms of implementation and knowledge around the LCA methodology, thus managing to overcome barriers that are often associated to these tools such as time constraints, data gaps etc. Especially for vehicle manufacturers limitations in relation to data gaps tend to be lower since customized product specific tools such as the International Material Database System (IMDS), provide a great potential for acquisition of primary data in terms of materials composition of the vehicle and its components. It has also been noted that, due to this system, the time for performing environmental assessments has been significantly reduced (Dahllöf L., 2013; Koffler et al., 2008). **Paper I** showed that companies with structured DfE processes were more familiar and had greater experience on using DfE tools in a systematic manner. Although limited interaction among product designers and DfE tools users was reported in the study, the opportunities for cooperation were higher when DfE was a formal process (combining both DfE expertise and tools).

To conclude, the results from **Paper I** indicate that greater efforts are needed so that DfE processes are formalized and that DfE tools are more systematically adopted and integrated into the product development processes of the studied companies. As result of current practices, a life cycle perspective is not sufficiently addressed and considered when design strategies are developed and introduced. Neither in terms of environmental requirements and life cycle thinking in material selection processes, nor in terms of DfE tools that could facilitate integration and increase understanding of emerging challenges. Thus, the risk for sub-optimizations and shift of environmental burdens along different life cycle stages remains apparent.

5.1.2 Availability of tools in literature

Paper II provided an overview of existing DfE tools. Findings from the paper are presented below answering the second research question, **RQ2**, *“What tools are available that can assist the systematic identification and assessment of design strategies for improved environmental performance of vehicles?”*

The literature review on DfE tools presented in **Paper II** resulted in a rich toolbox of 41 qualitative and quantitative DfE tools, of different levels of complexity and data demands. The identified tools are presented in Table 7. Based on the specific needs and degree of information that the user aims to obtain, different tools can be utilized and for different purposes. Product specific tools, aiming to assist vehicle design and development were also identified in the paper (Arena et al., 2013; Millet et al., 2012; Schöggel et al., 2014).

It has been previously noted that selection of DfE tools should among other things be based on informed choices (e.g. on the options available) as well as on specific needs of the users (Lofthouse, 2006; Ritzen & Lindahl, 2001). Moreover, DfE tools should manage to capture and assess environmental aspects that are relevant to the product (Byggeth & Hochschorner, 2006; Ernzer & Birkhofer, 2002; Lofthouse, 2006). Given the high number of tools available, companies need support in finding the most suitable DfE tools (Pigosso et al., 2013). Among the numerous reviews of DfE tools available by for instance Birch et al. (2012), Bovea & Perez-Belis (2012), Byggeth & Hochschorner (2006), Pigosso et al., (2015) and Tyl et al. (2014), none have been performed to approach specifically the vehicle design and development process, as the study presented in **Paper II**.

For this reason, and in order to assist the tools selection process during vehicle design and development, the identified tools were analyzed based on features of DfE tools that were identified as important and relevant to this product category. Examples include the ability to capture and monitor environmental impacts that are associated with vehicles, to have a life cycle perspective and to integrate customer and design requirements (see also Table 3, Section 4.2). These features were obtained from **Paper I** and previous research. The result of the analysis of the tools based on the selected features is provided in Table 7.

Environmental and life cycle performance considerations

The DfE tools included in the paper, manage to capture environmental constraints that are relevant from a vehicle design perspective (such as emissions of various pollutants and toxic substances, use of resources, the generation of waste and recycling aspects). The only aspect that was less commonly captured by the listed tools was noise. Similarly, most of the tools may consider the life cycle of the vehicle including activities related to manufacturing, use and final disposal. The majority of tools manage to cover multiple environmental aspects in a life cycle perspective while tools that focus on a single impact category or tools that focus on optimizing a certain life cycle stage were identified (for instance tools that assess EOL strategies). As different units in the vehicle manufacturing industry may need to address different environmental challenges, monitor different requirements or optimize specific properties of the vehicle, such specialized tools have the possibilities to provide relevant support, thus offering greater potentials for adoption and integration to the vehicle design and development process.

Multi-criteria perspective

Vehicle developers participated in the study presented in **Paper I** expressed a need for tools that would assist in adopting a multi-criteria perspective by combining different aspects and design requirements of the product, including functional, economic and environmental requirements but also regulations and standards, and customer demands. Results from **Paper II** indicated that such a multi-criteria perspective where DfE tools combine different design requirements and

constraints exists in many tools. A variety of combinations are available (as shown in Table 7) usually covering 2 to 3 different aspects at the same time.

Among the listed tools, possibilities to integrate multiple requirements are most often provided by tools that aim to identify design strategies. The environmental parameters in those tools are related to customer requirements (as for instance in the Environmental Quality Function Deployment (EQFD) and House of Ecology (HoE)) or functional properties of the product (as in the Eco-Functional Matrix). The majority of these tools originate from Quality Function Deployment (QFD) and similar methods that are commonly used during product innovation processes (Tyl et al., 2014). A limitation however, is that possibilities to assess the environmental performance of the identified strategies are not offered by these tools and for this reason the use of advanced or simplified assessment methods is required.

Fewer possibilities for a multi-criteria perspective were identified in tools for assessing design strategies. A few examples include the material selection tools by Ermolaeva et al. (2004) and Ribeiro et al. (2013) which consider environmental, economic and functional requirements and the CES Selector with Eco audit software (Granta Design, 2013). Although the latter covers a full range of relevant features, it lacks a detailed environmental assessment process.

Integration to engineering design tools

Paper II investigated also the availability of DfE tools that can be integrated or combined with traditional engineering design tools (such as weight optimization models or computer based design tools). Such tools may assist vehicle designers to obtain direct information on the feasibility or performance of the design alternatives not only in terms of technical specifications but also in relation to environmental aspects, and potentially increase the efficiency and effectiveness of the DfE process. In **Paper I** it was discussed that sector based material databases and material control lists were developed and integrated to the design processes and engineering tools. Among the DfE tools listed in **Paper II** however, only a limited number offer possibilities for tools integration. Due to the complexity of the product, facilitating such integration in current engineering tools in a reliable and efficient way is a challenge. Although there is an ongoing development towards software tools that combine computer aided design systems to environmental performance indicators, such as SolidWorks Sustainability and CES Selector with Eco Audit, there is no clear evidence about their use in industry.

Table 7 Analysis of the identified DfE tools based on the selected features

DfE tool	Input -output mechanism	Systems perspective		Multi-criteria approach				Trade-offs			Integration to engineering tools
		Life cycle thinking	Environmental constraints	Functions	Regulation	Customer	Cost	EN	LC	EN/OTH	
<i>Prescriptive tools</i>											
Ecodesign checklist	Qualitative and quantitative	Yes	Multiple	Yes	No	Yes	No	▪	▪	▪	No
Ten golden rules	Qualitative	Yes	Multiple	Yes	No	No	No				No
Material and Chemical Control Lists	Quantitative	No	Single	No	Yes	No	No				Yes
Ecodesign guidelines	Qualitative and quantitative	Yes	Multiple	Yes	(Yes)	(Yes)	No	▪	▪	▪	No
CSPD	Qualitative	Yes	Multiple	No	No	No	Yes	▪	▪	▪	
<i>Tools that identify strategies</i>											
LC-QFD	Semi Quantitative	Yes	Multiple	Yes	Yes	Yes	(Yes)	▪	▪	▪	No
EQFD	Semi Quantitative	(Yes)	Multiple	Yes	Yes	Yes	No	▪	▪	▪	No
Eco Functional matrix	Semi Quantitative	Yes	Multiple	Yes	No	Yes	Yes	▪	▪	▪	No
HoE	Semi Quantitative	(Yes)	Multiple	No	(Yes)	Yes	Yes	▪	▪	▪	No
CBR and TRIZ	Quantitative	(Yes)	Multiple	Yes	(Yes)	(Yes)	No	▪	(*)	▪	No
ARIZ-based life cycle engineering model	Quantitative	Yes	Multiple	Yes	(Yes)	(Yes)	No	▪	▪	▪	Yes
<i>Analytical tools (simplified assessment)</i>											
Eco Design Strategy Wheel	Qualitative	Yes	Multiple	Yes	No	No	No	▪	▪	▪	No
E-Concept Spiderweb	Qualitative	Yes	Multiple	Yes	No	Yes	Yes	▪	▪	▪	No
ABC Analysis	Qualitative	Yes	Multiple	No	Yes	No	Yes	▪	▪	▪	No
MECO	Qualitative and quantitative	Yes	Multiple	No	(Yes)	(Yes)	No	▪	▪	(*)	No
MET	Quantitative	Yes	Multiple	No	No	No	No	▪	▪		No
ERPA	Semi-Quantitative	Yes	Multiple	No	No	No	No	▪	▪		No
EEA	Semi-Quantitative	Yes	Multiple	No	Yes	Yes	No	▪	▪		No
ECO Design Pilot Assistant	Semi-Quantitative	Yes	Multiple	No	No	No	No	▪	▪		No
<i>Analytical tools (advanced assessment)</i>											
LCA	Quantitative	Yes	Multiple	No	No	No	No	▪	▪		Yes
LCA software	Quantitative	Yes	Multiple	No	No	No	No	▪	▪		No
E-LCC	Quantitative	Yes	Multiple	No	No	No	Yes	▪	▪	▪	No

DfE tool	Input –output mechanism	Systems perspective		Multi-criteria approach				Trade-offs			Integration to engineering tools
		Life cycle thinking	Environmental constraints	Functions	Regulation	Customer	Cost	EN	LC	EN/OTH	
LCDSM	Qualitative and quantitative	Yes	Multiple	No	No	No	No	•	•		Yes
ERA	Quantitative	(Yes)	Single	No	No	No	No				No
MCA	Qualitative and quantitative	(Yes)	Multiple	(Yes)	(Yes)	(Yes)	(Yes)	(•)	(•)	(•)	No
Material selection tool	Quantitative	Yes	Multiple	Yes	No	No	Yes	•	•	•	No
LCA framework for material selection	Quantitative	Yes	Multiple	Yes	No	No	Yes	•	•	•	No
CES Selector with Eco Audit™	Quantitative	Yes	Multiple	Yes	Yes	Yes	Yes	•	•	•	Yes
EcologiCAD	Quantitative	Yes	Multiple	Yes	No	No	No	•	•	•	Yes
GaBi DfX	Quantitative	Yes	Single	No	Yes	Yes	Yes	•	•	•	Yes
SolidWorks Sustainability	Quantitative	Yes	Multiple	Yes	No	No	No	•	•	•	Yes
EDST	Quantitative	No	Single	No	No	No	No			•	
<i>Analytical tools (Indicators)</i>											
ReSICLED	Quantitative	No	Single	No	Yes	No	Yes			•	(Yes)
Ecodesign indicators	Quantitative	No	Single	No	No	No	No				(Yes)
I.M.R.R.	Quantitative	No	Single	No	Yes	No	(Yes)			•	(Yes)
Environmental benchmarking	Qualitative and quantitative	(Yes)	Multiple or Single	(Yes)	(Yes)	(Yes)	(Yes)	(•)	(•)	(•)	(Yes)
MIPS	Quantitative	(Yes)	Single	No	No	No	No		(•)		(Yes)
CED	Quantitative	(Yes)	Single	No	No	No	No		(•)		(Yes)
OPM	Quantitative	Yes	Single	No	No	No	No		•		(Yes)
E2PA	Quantitative	Yes	Multiple	Yes	No	No	No	•	•	•	(Yes)
REACH, environmental economic indicators	Semi-Quantitative	No	Single	No	Yes	No	Yes			•	(Yes)
Vehicle development indicators	Qualitative and quantitative data	Yes	Multiple	No	Yes	No	Yes	•	•	•	(Yes)

Note: • indicates that the parameter is valid for the tool while (•) indicates that the parameter is valid for the tool but is highly dependent on selections and decisions of the user. CSPD= Checklist for sustainable product development; LC-QFD=Life cycle quality function deployment; EQFD=Environmental quality function deployment; HoE= House of ecology; CBR= Case based reasoning; TRIZ= Theory of Inventive Problem Solving; MECO=Materials, energy, chemicals, other; MET= Materials, energy, toxicity; ERPA= Environmentally responsible product assessment; EEA= Environmental effect analysis; LCA= Life cycle assessment; E-LCC=Environmental life cycle cost analysis; LCDSM= Life cycle design structure matrix; ERA= Environmental risk assessment; MCA= Multi criteria analysis; CAD= Computer aided design; DfX= Design for X; EDST= Environmental design support tool; ReSICLED=Recovery Systems modelling & Indicators Calculation Leading to End-of-Life-conscious Design; I.M.R.R.= Impact of modules on recyclability rate; MIPS= Material intensity per unit service; CED= Cumulative energy demand; OPM= Oli point method; E2PA=Environmental efficiency potential assessment; REACH=Registration, Evaluation, Authorization and Restriction of Chemicals

DfE tools implementation and development considerations

Overall the results of the paper showed that existing DfE tools manage to capture aspects that are relevant from a vehicle design and development perspective although omissions and limitations exist. None of the tools capture all suggested features. Moreover, and as DfE tools may entail simplifications (for instance focusing on specific environmental impacts or life cycle stages) the selection of tools should be based on the application as well as the relevance of the obtained information (Hochschorner and Finnveden, 2003). It was suggested in the paper that using a combination of tools is preferable in both cases to avoid sub-optimizations and problem shifting.

Data requirements associated to the different tools will very likely determine the implementation stage of the tool during product development. As a rule of thumb it is usually suggested that simplified assessments and eco-ideation tools are used at very early stages while detailed and advanced assessment towards the end. A paradox can be observed however, since some of the simplified assessment tools or tools that aim to provide design strategies might still require advanced and detailed knowledge about the product or results from for instance LCA studies in order to be able to provide a reliable outcome. In the study of Hochschorner and Finnveden (2003) but also in **Paper V** empirical evidence of this paradox is provided since quantitative data are used for the justification of scoring choices.

Successful practices among vehicle manufacturers however, provide an example of how data limitations can be minimized. It was discussed in **Paper I**, that with the establishment of sector based tools (e.g. materials monitoring tools) direct input of primary data can be provided to LCA and similar assessment methodologies. Based on this, the vehicle manufacturing industries have a great potential to increase the systematic use of assessment tools that, if combined with tools for identifying design strategies, will assist not only in facilitating the eco-innovation process but also in selecting strategies based on life cycle considerations.

From **Paper I** and previous findings (Ernzer & Birkhofer, 2002; Knight & Jenkins, 2009; Ritzen & Lindahl, 2001) it is concluded that product customized tools are more likely to be adopted and used in a systematic manner. Although development of product specific tools is ongoing (a few were listed also in this thesis) more efforts are needed in order to customize existing tools or develop new that better fulfill the needs of vehicle manufacturing industries, especially in terms of capturing relevant information and metrics but also in terms of integration to product development processes.

5.2 Assessing vehicle design strategies from a life cycle perspective

This section aims to answer the third research question of this thesis, **RQ3**: *“How do new design strategies for reducing fuel consumption affect the life cycle environmental performance of vehicles and what key factors should be in focus when new design strategies are assessed?”*

This thesis looks at the life cycle environmental consequences of two different design strategies for reducing fuel consumption; reducing the weight of the vehicle (assessed in **Paper III** and **IV**) and using alternative propulsion i.e. an electric drivetrain (assessed in **Paper V**). Both strategies offer considerable advantages in lowering the energy use and CO₂ emissions during the

operation stage of the vehicle. At the same time, however, new challenges emerge that can potentially lead to problem shifting situations, i.e. situations when one environmental aspect or life cycle stage is improved at the expense of another. The factors that are expected to influence the extent of these shifts and potential trade-offs are discussed along with the implications to the vehicle design and material selection processes.

The case studies

Lightweight design was assessed in two material selection LCA case studies presented in **Paper III** and **Paper IV** respectively. In **Paper III** current material alternatives used for a heavy truck exterior panel were assessed and compared to SrPET which is a novel material. The current material alternatives included a glass fiber reinforced unsaturated polyester (SMC) and an unreinforced thermoplastic material, (polycarbonate/poly (ethylene terephthalate), PC/PET). SMC is a thermoset composite material with limited recycling possibilities while PC/PET although recyclable, has considerably poorer mechanical properties. SrPET was assessed as a potential alternative for this specific component due to weight reduction possibilities exhibiting higher specific stiffness compared to PC/PET and increased recyclability compared to SMC.

The second material substitution study (**Paper IV**) concerned the life cycle environmental performance of a roof of a heavy truck. The roof was designed as a sandwich structure and six different material alternatives were evaluated; two metals (steel and aluminium) that are common for vehicle applications, two composite materials (carbon fiber reinforced vinyl-ester (C/VE) and glass fiber reinforced vinyl-ester (G/VE)) that are also widely used, the novel SrPET composite, and unreinforced PET. The main purpose of the case study was to test the material selection approach that is presented in the same paper (described further in Section 5.3), which is done through a theoretical case of a non-existing product.

The truck panels and roof were assumed to be used by a diesel truck weighing 40tn and covering a life time distance of 1,000,000 km. The reference scenario for EOL treatment of the panels in **Paper III** was assumed to be incineration with energy recovery of the thermoplastic SrPET and PC/PET panel and landfill of the SMC panel. In **Paper IV**, the truck roofs made of metals and thermoplastic materials were assumed to be recycled while the ones made of thermoset composites were incinerated. Benefits of the recovered materials and electricity were modelled as avoided burdens i.e. replacing the production of primary material and electricity. The environmental performance of the panels and roof was assessed in terms of CED and GWP.

In **Paper V** two drivetrain technologies were assessed through a case study of two prototype vehicles; an internal combustion and an electric vehicle. The two prototypes were identical in terms of body construction which made it possible to exclude those parts and focus only on the differences of the vehicles which were identified in the drivetrains. The benefit of this was the ability to highlight important variations between lifecycle stages that resulted as a change of the drivetrain technology. The two drivetrains were assessed using the semi-quantitative method ERPA (described in Section 4.4.2). It was assumed for the study that the two drivetrains have the same function with equal lifetime and range. The ICEV uses gasoline during operation while for EV the Swedish electricity mix was assumed to be used in order to charge the batteries. During EOL the study assumes that the drivetrains are collected and handled in Sweden following the Swedish EOL management practices (Tasala Gradin et al., 2013); the drivetrains are detoxified,

shredded and divided into fractions. The magnetic and heavy fractions are melted and down cycled while the light fraction is landfilled.

Additional features of the case studies have been presented also in Sections 4.4.1.1 and 4.4.2. A detailed description of the inventory data and underlying assumptions is provided in the respective papers. Although the three studies vary significantly (in terms of scope, method used etc.) they collectively provide useful insights about the aspects that could influence the environmental performance of vehicles.

New vehicle design strategies and emerging trade-offs

As expected, the lighter alternatives exhibited the lowest impact in terms of lifetime energy demands and GWP in both lightweight design cases studies. For all material alternatives, the use phase accounted for the biggest proportion in both impact categories followed by the manufacturing phase. Given the assumptions related to the EOL alternatives, that stage had only a minor contribution to the life cycle energy demands and GHG emissions.

Variations in the relative importance of the use and manufacturing stages indicated the potential for trade-off and problem shifting between different life cycle stages of the vehicle. These variations were more apparent by the results obtained in **Paper IV**. The steel roof in **Paper IV** was the heaviest one exhibiting the highest life cycle CED and GWP. Almost 95% of that impact was attributed to the use phase. For the lightest and best performing C/VE or aluminium structures the share of the use phase was slightly higher than 50% with the majority of the remaining impacts occurring during manufacturing. The impact during manufacturing of the lightest structures was increased not only in relative terms but also in absolute numbers. The energy requirements during manufacturing of the C/VE structure were almost 4 times higher than steel resulting also in 3 times more GHG emissions. Similar results were obtained for the remaining materials (see also Table 7 in **Paper IV**). The only case where such a trade-off did not occur was in the comparison between SMC and SrPET exterior panel of a truck in **Paper III** which showed that the lighter material (SrPET) not only decreased the impact during the use phase but also performed better during the manufacturing stage.

In line with previous research the findings of **Paper III** and **IV**, illustrate the potential benefits and limitations in terms of environmental performance when lightweight design alternatives are considered. As shown by for instance Koffler (2014) and Duflou et al. (2012) significant savings in terms of life cycle energy demand and GHG emissions can be achieved. In addition, Koffler (2014) showed that the lightweight GFRC alternative considered in his study, resulted in greater energy demand during the materials and part production stage compared to the steel alternative. Kim et al. (2010) draw the same conclusions when lightweight design using aluminum and high strength steel was considered, indicating that the lighter design alternatives resulted in higher impact during manufacturing. Similarly to **Paper III**, however, results indicating energy and emissions savings during manufacturing stages are also available (Duflou et al., 2012).

The results of this thesis confirm previous studies and illustrate the importance of lightweight design as a means to reduce the energy and GHG emissions during the use phase of the vehicle. Due to the risk of problem shifting when lighter materials are used, the importance of life cycle considerations is demonstrated. Moreover, as benefits and limitations of lightweight materials

can be case specific, this thesis makes apparent the need for integrated and systematic assessments in standard material selection processes.

A similar shift between the use and manufacturing stages has been identified for the ICEV and EV drivetrains assessed in **Paper V**. The ICEV exhibited poorer environmental performance during the use phase, in comparison to the EV. The opposite result was obtained for the manufacturing stage. Quantitative assessments on EVs provided by for instance Hawkins et al. (2013) and Ma et al. (2012) draw same conclusions. In **Paper V**, the low performance of the electric drivetrain during pre-use stages was mainly due to the materials needed and especially the use of critical materials such as REEs found in the permanent magnet. REEs require energy intense extraction and manufacturing processes (Ali, 2014). Mining of REEs has also been associated with releases of toxic and radioactive materials resulting in significant threats for human health and ecosystem's toxicity (ibid). Thus, for EVs the associated trade-offs are not only between the different life cycle stages but also between different environmental impacts as also indicated by Hawkins et al. (2013).

Paper V highlights the difference between the two drivetrains in terms of material composition something that is less often discussed in the literature (Messagie et al., 2014). Such a result has significant implications in the ways that vehicles and new design strategies are currently evaluated and compared. It was discussed in **Paper V** that although the most common way to compare the performance of vehicles today is in terms of energy demands and CO₂ emissions these metrics may no longer be appropriate to capture emerging challenges and environmental impacts associated to EVs. This observation may also be relevant for the case of lightweight design and new advanced materials for which little information in relation to their life cycle environmental performance is currently available.

EOL considerations

Given the selected impact categories and assumptions related to treatment processes, the EOL stage exhibited the lowest impact of all stages in the case studies of **Papers III** and **IV**. It remains, however, an important stage in the lifecycle of the vehicle. Due to regulatory demands on ELVs, vehicle manufacturers would need to consider replacing materials that are not recyclable and provide solutions that comply with those demands. Although ELV refers to passenger cars and light duty vehicles only, truck as well as rail vehicle manufacturers seem to be highly affected due to increased demands posed by their customers as seen in **Paper I**.

The potential benefits of recycling compared to other EOL treatment methods are illustrated through the findings of **Paper III** and **IV**. In both studies recycling resulted in greater energy and GHG emissions saving potentials compared to incineration and landfill where no energy or material recovery was assumed. As seen in **Paper IV** for instance, recycling of the aluminium truck roof may potentially reduce the total energy requirements by 30% while recycling of the thermoplastic PET and SrPET truck roofs by about 15%. Recycling of the thermoset composites (C/VE, G/VE and SMC) was not investigated in the case studies of this thesis, the main reason being that recycling practices for carbon fiber or glass fiber composite materials are still under development and at a cost that it does not allow composites recycling to be considered an attractive option today (Pimenta & Pinho, 2011; Yang et al., 2012). Studies on composites recycling however, demonstrate the lower energy intensity of recycled compared to virgin

materials (Howarth et al., 2014; Witik et al., 2013) indicating the potentials to minimize the life cycle impact of these materials.

For plastic and composite materials, incineration is often considered as a way to deal with waste volumes and at the same time recover energy. When incineration of the truck panels and roofs was concerned, especially for GWP, the case studies showed that the process impact is higher than the potential benefits of incineration. Despite having been described as “worst case” in **Paper IV**, landfill of plastics in terms of GHG emissions can be regarded as a better alternative than incineration, a conclusion that is also supported by Björklund and Finnveden (2005) and Eriksson and Finnveden (2009). Considering the waste management hierarchy (Directive 2008/98/EC, 2008) however, landfill is the least preferable option whereas recycling is promoted as among the most preferable alternatives.

The study performed in **Paper V** showed also that the low environmental performance of the EV was a result of the low recovery and recycling potential of the materials found in the electric drivetrain. Previous studies have reported great potentials for energy savings when EV components, for instance traction batteries, are recycled (Dunn et al., 2015; Messagie et al., 2014). Similar benefits have been reported for the case of composite materials as shown in **Paper III**, **Paper IV** and previous research (Howarth et al., 2014; Witik et al., 2013), highlighting the potentials of more circular product systems.

For recycling to be a meaningful practice however, not only need the materials and components in vehicles to be recyclable and designed in a way that makes it possible to be separated and recycled or recovered, but also technologies and platforms to manage these materials in efficient and cost effective ways need to be established. As products tend to become more complex, consisting of more advanced and heterogeneous materials, current EOL practices can be expected to be less appropriate in the future. This entails numerous challenges and uncertainties in relation to the ways that EVs and new more complex drivetrains and vehicle designs will be managed at their EOL (Elwert et al., 2016).

Influencing factors

Results from accounting LCA studies (like the ones performed in this work) usually provide a “snapshot” of the environmental performance of the product that is associated to the underlying assumptions of each study. Similarly in **Papers III** and **IV**, the environmental performance of lightweight strategies was estimated based on certain assumptions as regards different lifecycle conditions. From the sensitivity analysis performed in **Paper IV**, it was derived that assumptions in relation to use phase of the vehicle (and consequently component) such as operational life and fuel consumption are expected to influence the life cycle environmental performance of the vehicle and therefore the significance of the identified trade-offs.

Paper IV for instance demonstrated that the benefits from lightweight materials increase as the assumed lifetime distance increases. For a short lifetime distance (up to 200,000 km), as shown in Figure 5, the heavier structures made of steel or thermoplastic polymers perform better due to their low impact during the manufacturing stage. As the travelled distance increases, lighter materials compensate for their energy intense production as shown also by Kim et al. (2010). If more energy efficient engines (for example EVs) are assumed the relative importance of the use phase would be reduced. Considering Figure 5, the gradient of the plotted lines will decline. This implies that all breakeven points between materials (i.e. the points when two materials exhibit

the same performance) would move to longer distances which would make the benefits of lighter materials to be less obvious.

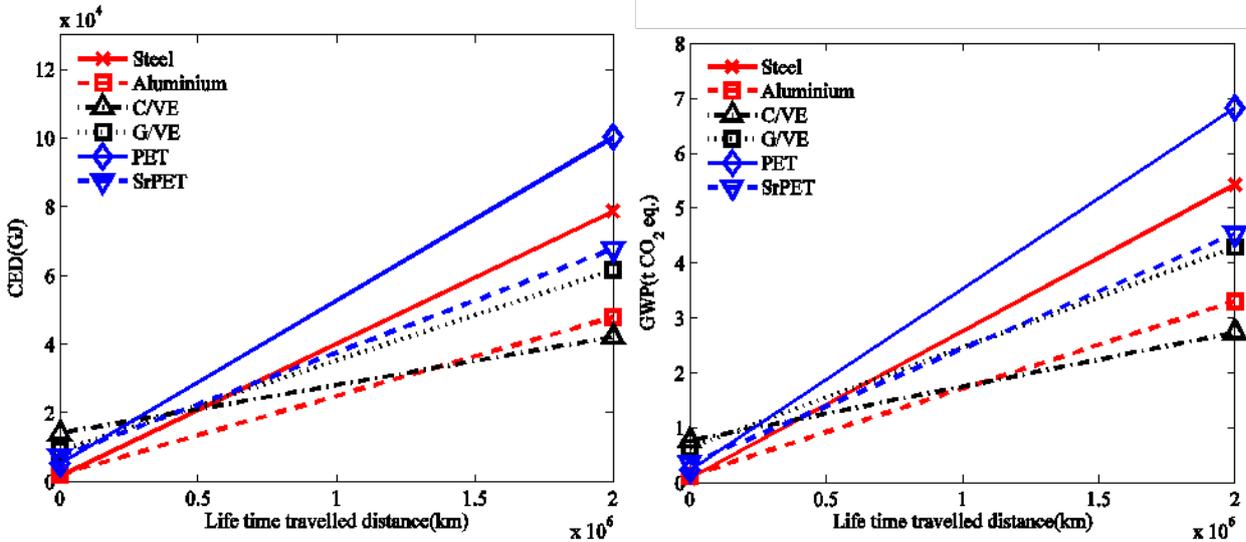


Figure 5 Influence of life cycle driving distance on CED and GWP for a diesel truck (Paper IV). Note: The values in the vertical axis of the CED figure should have been $\times 10$ instead of $\times 10^4$

The travelled distance seems to also influence the results relating to EV technologies as reported by Faria et al. (2013) and Egede et al. (2015). For the case of EVs, however, the carbon intensity of the electricity mix, used to supply traction energy, is the most influencing factor that determines not only the total impact of the EV but also the actual emissions savings during the use phase compared to ICEVs (Faria et al., 2013; Hawkins et al., 2013; Lewis et al., 2014; Ma et al., 2012). In **Paper V**, the Swedish electricity mix (that is based on hydropower and nuclear energy) was assumed to provide power to the electric drivetrain. A more carbon intense electricity mix would decrease the difference among the two drivetrains during the use phase, making the benefit of the EV less apparent. The method used in **Paper V** however, did not allow for a quantitative assessment of the influence that different electricity mixes may have on the environmental performance of the electric drivetrain and the associated savings compared to the ICEV. Hawkins et al. (2013), estimated that the amount of CO₂ emissions per km can be more than 3 times higher when a fossil fuel based electricity mix is used (e.g. from lignite combustion) compared to renewable sources (for example wind power).

5.3 Contribution to method development

Last but not least this thesis aims to contribute to method development by facilitating the use of environmental impact assessment methodologies during product design and material selection processes. The final research question, **RQ4**, “How can environmental assessment tools be integrated during product design and material selection processes?” is answered through the findings of **Paper IV**.

Previous research suggests that material selection is rarely based on processes that consider both functional and environmental properties in an integrated manner something that was also discussed in **Paper I**. Such practices however, often lead to sub-optimizations and shifts of

environmental burdens among different impact categories or life cycle stages as already shown by the results of **Papers III-V** in line with previous research. If life cycle improvements are aimed for, information on the factors influencing the life cycle environmental performance of the vehicle need to be considered and monitored early in the design stages.

In **Paper IV**, an integrated material selection approach is introduced, in which environmental LCA is incorporated in the traditional material selection process with the aim to allow for systematic evaluation of material alternatives before any final design decision. The suggested approach is illustrated in Figure 6.

The life cycle design approach suggested in **Paper IV** consists of five major steps; (1) Definition of design target, (2) Selection of material families and candidate materials, (3) Weight minimization, (4) Life cycle modelling and assessment, and (5) Results analysis and Material selection. Steps (1) to (3) are commonly applied in tradition material selection models (Ashby, 2011; Farag, 2014). The suggested approach however, builds on these models and expands their scope especially when the environmental performance of the materials is concerned (Step 4).

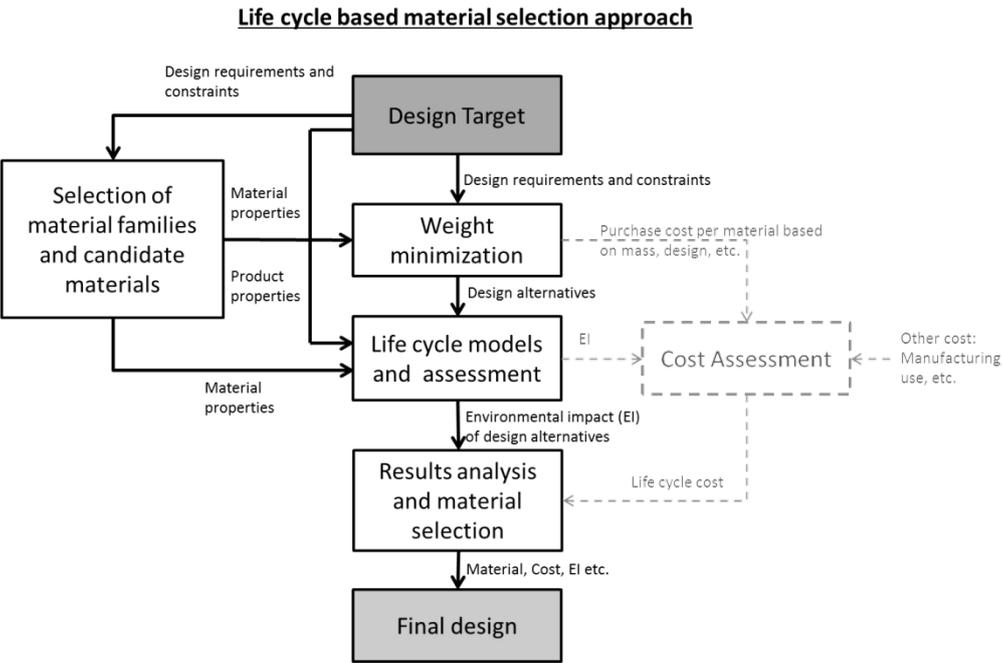


Figure 6 Framework for life-cycle based materials selection as developed and presented in Paper IV. The dashed lines show processes that are outside the scope of the suggested approach but could be included in the model.

The approach provides a generic guide to vehicle designers, while selection of weight minimization models, environmental analysis tools and impact assessment indicators can be decided by the users. In the case study provided in the same paper, LCA was modelled using the software tool SimaPro and generic databases that were available to the authors of the paper. The impact assessment methods selected (CED and GWP) captured two impact categories although in a real material selection situation, the users are given the freedom to select the ones that better fulfil their needs. Availability and quality of data will also determine the selection of the most appropriate impact assessment method. As different methods may lead to different

outcomes, it has been suggested by Bovea and Gallardo (2006) and Simões et al. (2011) that a variety of methods are applied before decision making on material selection or substitution.

Through the case study presented in **Paper IV**, possible ways to analyze and interpret the results are suggested. Suggested aspects to consider included: (1) total life cycle impact of each material alternative separately and in comparison to the others, (2) environmental performance of each alternative in different life cycle stages, (3) trade-offs between life cycle stages or environmental impact indicators and (4) variations in the design target or properties of the product and its life cycle that may influence the life cycle impact of the material. Selection of the optimal material is case specific, depending on company priorities of trade-offs between functional requirements.

Although cost is an important parameter, it was not considered in this approach. Cost constraints are already integrated in material selection today. Emphasis is given to the environmental parameter that although it is not new, it is still not prioritized. Previous studies may indicate the ways that cost can be integrated in a life cycle design material selection process (Ermolaeva et al., 2004; Giudice et al., 2005; Simões et al., 2013).

In relation to the tools available (as discussed and presented in Section 5.1.2), the approach fills the gap of integrated and multi-criteria models (shown in **Paper II**) where environmental assessment tools are combined with traditional engineering design tools such as weight optimization models. The suggested approach is expected to be closer to how the material selection process is performed during vehicle design today, thus adoption and implementation can be easier. As seen from **Paper I**, environmental expertise exists in some of the companies thus the competence needed is already available. Finally, by suggesting this integrated approach where different expertise is required (both from vehicles designers and DfE specialists), communication and co-operation during product design is enhanced.

Among the novel aspects of the suggested approach is that structural weight minimization is used as a means to acquire relevant information for the LCA models. Since no details on product specifications are available at that stage, engineering design tools may assist to bridge that data gap. With such a combination, information on the environmental performance of the product or design alternative is provided to vehicle designers along the selection process allowing for more comprehensive decisions that consider both functional and environmental properties of the design target.

5.4 Contributions and limitations of the thesis

The research questions raised throughout this work directed me to the use of a combination of qualitative and quantitative methods as described in Chapter 4. While the selected research approach assisted in obtaining relevant results that manage to fulfil the aims of the appended papers and thesis, the methods used have both advantages and limitations that are important to consider. Moreover, methodological and scoping choices can be expected to affect the outcome of the study and need to be discussed.

The interview study presented in **Paper I** contributed with valuable empirical data in relation to DfE implementation among vehicle manufacturing industries. Although the literature on

frameworks and success factors is rich, studies that investigate the use of them in practice as well as company specific case studies are rather scarce (Boks & McAloone, 2009). Elements that have been previously identified as important for a successful DfE approach such as integrated processes and tools (Hallstedt et al., 2013; Johansson 2002; Tingström, 2007) have been investigated in the aforementioned paper. This assisted in providing a comprehensive picture and understanding on potential links and relations among those elements. The results of the study however are rather case specific and cannot be generalized for all vehicle manufacturing industries or for other sectors. Yet, they agree to a large extent with previous findings and can be used to assist the adoption of DfE practices and tools among industry in general. As such the study is of relevance for both DfE researchers as well as DfE practitioners.

The compilation and analysis of the DfE tools in **Paper II** is expected to assist the tool selection process of the vehicle manufacturing industry. Features that have been identified as relevant for this product category are highlighted. As mentioned, the high number of DfE tools makes a comprehensive presentation difficult. Moreover, new tools and frameworks are constantly developed. Therefore, omissions in relation to the available tools certainly exist. The study however, aimed to capture key methodological combinations and to provide a representative list of the options available. This list can be expanded and supplemented based on the respective needs of the companies. The list can also be of use for other sectors that have similar design constraints.

Based on the findings from **Paper III** and **Paper IV**, the thesis demonstrated the potential trade-offs that may occur as a result of light weight design. From a DfE perspective both studies and **Paper IV** in particular contribute to the development of a DfE mind-set during material selection for the automotive industry. The papers show that it is possible even at early development stages to obtain information on the environmental performance of a design alternative and to use this information during decision making. An additional contribution of **Paper III** in particular is the information provided in relation to the environmental performance of the newly developed SrPET material. This first assessment assisted in providing inventory data in relation to the manufacturing process of this material but also into benchmarking its overall performance (environmental and functional) in relation to existing and commonly used materials.

LCA however, is a data demanding tool and it usually involves simplifications (Moberg et al., 2014). The degree to which such simplifications affect the result of the study needs to be discussed. A major simplification adopted in both papers concerns the selection of impact assessment indicators. From the broad list of indicators and impact assessment methodologies available two indicators were used, CED and GWP, assessing resource and GHG emissions intensity. Although both metrics are widely used when composite materials are assessed (Das, 2011; Duflo et al., 2012) such a simplification entails a risk that important information is omitted or overlooked (Bovea & Gallardo, 2006; Moberg et al., 2014). Manufacturing processes of synthetic composite materials may for instance give rise to impacts related ecosystem's and human toxicity due to the increased use of solvents and other chemicals (La Rosa, Cozzo, Latteri, Recca, et al., 2013; La Rosa, Cozzo, Latteri, Mancini, et al., 2013).

In terms of data quality, it should be noted that both **Paper III** and **Paper IV** include generic data. Although in **Paper III** primary data were used to cover most foreground processes, less information was available for the newly developed SrPET material. This limitation however, can

be expected, as the material is not currently in production. More optimized design and manufacturing processes have the potential to lead to lower energy requirements. **Paper IV** relies only on generic data since a theoretical case is presented. Although representative processes were selected, the outcome of the study in absolute terms is rather context depended. The limitation in relation to the SrPET material relates also to this study as little information on manufacturing routes is available.

Finally, the environmental assessment presented in **Paper V** demonstrates the key differences among the two drivetrain technologies and discusses the importance of developing relevant metrics for their comparison and assessment. ERPA however, is a qualitative tool and as such it can be considered to contain more arbitrary elements compared to quantitative assessments (Hochschorner & Finnveden, 2003). Among qualitative methods and tools, ERPA provides sufficient documentation in relation to the scoring system that in combination to primary and quantitative data used during the justification process may reduce the limitation of vagueness or subjectivity. Certain assumptions and simplifications as for example in relation to the electricity mix, batteries composition or EOL treatment processes etc. can be expected to influence the overall outcome as discussed in the paper.

Together **Papers III, IV and V** demonstrated that the choice of materials may have a significant impact on the life cycle environmental performance of newly developed vehicles. Irrespective of the design strategy adopted the environmental impact during manufacturing stages is expected to increase in relative importance accompanied by the recyclability challenge during the EOL stage. In this thesis, the different design strategies have been considered and assessed in isolation something that is not likely to happen in practice. Lightweight design is expected to influence the life cycle environmental (and economic) performance of an ICEV and an EV differently, thus influencing also the criteria applied during material selection processes.

6. Conclusions and recommendations for future work

The aim of this thesis is to increase understanding on the ways that vehicle design strategies has been and can be assessed from an environmental and life cycle perspective. The research focuses on lightweight design and electric drivetrains as two of the major design strategies adopted today. Through case studies the potential of these strategies to improve the life cycle environmental performance of vehicles is assessed. Moreover, this thesis aims at contributing to the development of a systematic and integrated approach for materials selection as a means to increase the systematic consideration of environmental parameters during design processes. The main conclusions are presented below.

A. Map and increase understanding on the current practices and available tools

It can be concluded from the findings of this thesis that the maturity, regarding adoption and implementation of DfE practices, varies among vehicle manufacturing industries in Sweden. As a consequence, the ways that design strategies (aiming to improve the environmental performance of vehicles) are identified and assessed vary too. Although the studied companies are aware of the major environmental challenges in relation to their products and work intensively to fulfil the increasing regulatory requirements, environmental considerations during product development processes, and in particular during material selection, often lack a holistic lifecycle perspective.

When the adoption of supporting DfE tools is concerned, significant differences among the companies exist, especially in terms of maturity, experience and degree of systematic use of such tools. Prescriptive tools that manage and monitor regulatory requirements have succeeded in becoming an integrated part of the product development process in all studied companies while the use of analytical tools is less formalized. Even for the tools available in the companies their full potential has not been exploited, as results from such tools were quite seldom used to determine a DfE design strategy.

This thesis showed, however, that a rich and diverse toolbox is available and different tools can be considered suitable to be used for this product category. More than 40 DfE tools were listed and analyzed aiming to assist vehicle developers to the DfE tools selection process. The identified tools vary in terms of complexity and offer different possibilities to capture aspects that have been identified as important from a vehicle design perspective such as the ability of the tool to monitor environmental impacts associated with this product category, life cycle considerations, customer requirements and more. Although these aspects were covered in many tools and in various combinations, none of the tools manage to fulfil all of them. The use of a combination of tools is encouraged that would assist vehicle developers to obtain comprehensive information on the most important aspects that need to be monitored during the different stages of vehicle design and development.

B. Assess vehicle design strategies from a life cycle perspective

The fact that design strategies are not sufficiently assessed increases the risk of problem shifting situations and sub-optimizations. From the findings of the case studies and the sensitivity analyses performed it can be concluded that there is often a trade-off among savings in use phase and the manufacturing stage of the vehicle, when it comes to new vehicle design strategies aiming at reducing the energy use during the operation stage. This trade-off occurs, both when

lightweight design or electric drivetrains are concerned. The estimated level of these trades-offs however, depends on the underlying assumptions of the study and especially the ones concerning the operational life of the vehicle, fuel efficiency and alternative fuels or for the case of EV, the carbon intensity of the energy supply mix.

It becomes apparent from the findings of this thesis that despite its low share in terms of environmental impact, EOL has an important role in the overall environmental performance of vehicles which is expected to increase in the future. For the case of lightweight materials and EVs long lifetimes are suggested in order for the benefits of these strategies to be fully exploited. As this is something that cannot be guaranteed or predicted, efficient designs, but also efficient manufacturing processes and improved (and most important in place) recycling systems can be proven to be even more influential towards minimizing the environmental impact of vehicles. Thus, for long term gains and for a sustainable transport sector, improvements during the use phase of the vehicle would be of less value unless both up-stream (pre use) and down-stream (after use) processes are also improved.

Thinking of the complete life cycle of the design alternatives already at the early product development stages would assist in identifying environmental hotspots and potential trade-offs. Moreover, relevant metrics need to be considered. Findings from this thesis indicate that new challenges may emerge especially for the case of EVs and advanced materials that current assessment practices might not be able to capture.

C. Contribute to method development for improved life cycle environmental performance of vehicles

With processes that integrate environmental analysis tools to traditional product design models, there is a higher possibility that design strategies will be assessed and alternatives will be evaluated before final decisions. Such an approach for material selection is presented in this thesis. The suggested approach follows traditional material selection models adding the environmental assessment process as part of the material evaluation step. Design tools such as weight optimization may provide necessary information to the assessment process when limited information about product characteristics is available. The suggested approach offers customization freedom to the users that is expected to facilitate its adoption and makes it adaptable to the needs of the design target and associated impacts. With such an integrated material selection process possibilities for life cycle consideration are increased while omissions and the risk for sub-optimization are eliminated. Finally, cooperation and learning processes are encouraged as the approach integrates a variety of competences including engineer designers, material experts and environmental specialists.

6.1 Recommendations for future work

The scope of **Paper I** was limited to looking only at the product development process and to the degree that life cycle environmental considerations have been integrated into that process. Future research may consider expanding this scope by considering all stakeholders (customers, investors, regulators, financial departments, procurement etc.) that in one way or another influencing the business and environmental goals of the company. Mapping these different flows of information may assist in increase understanding on the potential synergies and conflicts

among the requirements expressed by the different actors which may facilitate or hinder eco-innovation activities in the vehicle manufacturing industry in Sweden.

An obvious extension of the environmental assessments presented in **Papers III** and **IV** could be to include a broader range of environmental impact assessment methods and indicators. This would lead to a more comprehensive assessment of composite materials thus assist in identifying emerging sources of environmental impacts and potential trade-offs.

If the material selection approach presented in **Paper IV** were tested in practice and in actual vehicle design and development processes, insights in relation to the factors (both in terms of processes and people) influencing deployment, efficiency and the overall success of the approach could be obtained. This result may facilitate adoption and systematic use of DfE tools during material selection that would eventually lead to more informed material choices.

This thesis discusses vehicle design strategies based on traditional business models that have a strong focus on the final product provided. However, the interest and development towards more function or service oriented business models, the so called Product Service Systems (PSS), has increased also in the case of the automotive industry. Compared to traditional models, products in PSS are designed for remanufacturing and for longer lifetimes. Life cycle considerations are thus essential in PSS models. This research can be expanded, to investigate the implications that such a business model shift may have on the ways that vehicles and transport solutions in general, are designed and developed. The results may highlight the potential contribution of PSS towards more sustainable product systems and the associated impact of this transition in terms of innovation of transport services but also in terms of regulation and policy making.

References

- Alcock, B., & Peijs, T. (2013). Technology and Development of Self-Reinforced Polymer Composites. *Polymer Composites - Polyolefin Fractionation - Polymeric Peptidomimetics - Collagens*, 251, 1-76.
- Ali, S. (2014). Social and Environmental Impact of the Rare Earth Industries. *Resources*, 3(1), 123.
- American Chemistry Council Inc. (2010). Global Automotive Declarable Substance List (GADSL). Retrieved September, 2016, from <http://www.gadsl.org/>
- Andersson, M., Ljunggren Söderman, M., & Sandén, B. A. (in press). Are scarce metals in cars functionally recycled? *Waste Management*.
- Arena, M., Azzone, G., & Conte, A. (2013). A streamlined LCA framework to support early decision making in vehicle development. *Journal of Cleaner Production*, 41, 105-113.
- Asensi, I. R. (2016). The carbon fiber makes its way in the automotive industry. *Reinforced Plastics*.
- Ashby, M. F. (2009). *Materials and the environment: eco-informed material choice*. Oxford, UK: Butterworth-Heinemann.
- Ashby, M. F. (2011). *Materials selection in mechanical design* (Fourth ed.). Oxford, UK: Butterworth-Heinemann.
- Bauman, H., & Tillman, A.-M. (2004). *The hitch hiker's guide to LCA: an orientation in life cycle assessment methodology and application*. Lund, Sweden: Studentlitteratur.
- Baumann, H., Boons, F., & Bragd, A. (2002). Mapping the green product development field: engineering, policy and business perspectives. *Journal of Cleaner Production*, 10(5), 409-425.
- Bey, N., Hauschild, M. Z., & McAloone, T. C. (2013). Drivers and barriers for implementation of environmental strategies in manufacturing companies. *CIRP Annals - Manufacturing Technology*, 62(1), 43-46.
- Bhamra, T. A. (2004). Ecodesign: The search for new strategies in product development. *Proceedings of the Institution of Mechanical Engineers, Part B: Journal of Engineering Manufacture*, 218(5), 557-569.
- Bhander, G. S., Hauschild, M., & McAloone, T. (2003). Implementing life cycle assessment in product development. *Environmental Progress*, 22(4), 255-267.
- Birch, A., Hon, K. K. B., & Short, T. (2012). Structure and output mechanisms in Design for Environment (DfE) tools. *Journal of Cleaner Production*, 35, 50-58.
- Björklund, A., & Finnveden, G. (2005). Recycling revisited—life cycle comparisons of global warming impact and total energy use of waste management strategies. *Resources, Conservation and Recycling*, 44(4), 309-317.
- Bocken, N. M. P., Allwood, J. M., Willey, A. R., & King, J. M. H. (2011). Development of an eco-ideation tool to identify stepwise greenhouse gas emissions reduction options for consumer goods. *Journal of Cleaner Production*, 19(12), 1279-1287.
- Boks, C. (2006). The soft side of ecodesign. *Journal of Cleaner Production*, 14(15-16), 1346-1356.
- Boks, C., & McAloone, T. C. (2009). Transitions in Sustainable Product Design Research. *International Journal of Product Development*, 9(4), 429-449.
- Bovea, M. D., & Gallardo, A. (2006). The influence of impact assessment methods on materials selection for eco-design. *Materials & Design*, 27(3), 209-215.

- Bovea, M. D., & Perez-Belis, V. (2012). A taxonomy of ecodesign tools for integrating environmental requirements into the product design process. *Journal of Cleaner Production*, 20(1), 61-71.
- Brones, F., & Monteiro de Carvalho, M. (2015). From 50 to 1: integrating literature toward a systemic ecodesign model. *Journal of Cleaner Production*, 96, 44-57.
- Byggeth, S., & Hochschorner, E. (2006). Handling trade-offs in ecodesign tools for sustainable product development and procurement. *Journal of Cleaner Production*, 14(15-16), 1420-1430.
- Cheah, L. W. (2010). *Cars on a Diet: The Material and Energy Impacts of Passenger Vehicle Weight Reduction in the U.S.* (Doctoral thesis), MIT, Massachusetts Institute of Technology Massachusetts, USA.
- Ciravegna Martins da Fonseca, L. M. (2015). ISO 14001:2015: An improved tool for sustainability. *2015*, 8(1), 14.
- COM (2001) 68. (2001). Green paper on Integrated Product Policy: Commission of the European Communities.
- Cullbrand, K., & Magnusson, O. (2011). *The Use of Potentially Critical Materials in Passenger Cars.* (Master thesis), Chalmers University of Technology, Gothenburg, Sweden.
- Dahlöf L. (2013). *How the chemical and material management in the automotive industry became a quality improver for LCA in the Volvo Group.* Paper presented at the 6th International Conference on Life Cycle Management, Gothenburg
- Das, S. (2011). Life cycle assessment of carbon fiber-reinforced polymer composites. *The International Journal of Life Cycle Assessment*, 16(3), 268-282.
- Dekoninck, E. A., Domingo, L., O'Hare, J. A., Pigosso, D. C. A., Reyes, T., & Troussier, N. (2016). Defining the challenges for ecodesign implementation in companies: Development and consolidation of a framework. *Journal of Cleaner Production*, 135, 410-425.
- Deutz, P., McGuire, M., & Neighbour, G. (2013). Eco-design practice in the context of a structured design process: an interdisciplinary empirical study of UK manufacturers. *Journal of Cleaner Production*, 39, 117-128.
- Directive 2000/53/EC of the European Parliament and of the Council of 18 September 2000 on end-of life vehicles (2000).
- Directive 2002/95/EC of the European Parliament and of the Council of 27 January 2003 on the restriction of the use of certain hazardous substances in electrical and electronic equipment (2002).
- Directive 2006/66/EC of the European Parliament and of the Council of 6 September 2006 on batteries and accumulators and waste batteries and accumulators and repealing Directive 91/157/EEC (2006).
- Directive 2009/125/EC of the European Parliament and of the Council of 21 October 2009 establishing a framework for the setting of ecodesign requirements for energy-related products (2009).
- Directive 2008/98/EC of the European Parliament and of the Council of 19 November 2008 on waste and repealing certain Directives. (2008).
- Dominick, P. G., Demel, J. T., Lawbaugh, W. M., Freuler, R. J., Kinzel, G. L., & Fromm, E. (2001). *Tools and tactics of design.* New York;Chichester: Wiley.
- Duflou, J. R., Deng, Y., Van Acker, K., & Dewulf, W. (2012). Do fiber-reinforced polymer composites provide environmentally benign alternatives? A life-cycle-assessment-based study. *MRS Bulletin*, 37(04), 374-382.

- Dunn, J. B., Gaines, L., Kelly, J. C., James, C., & Gallagher, K. G. (2015). The significance of Li-ion batteries in electric vehicle life-cycle energy and emissions and recycling's role in its reduction. *Energy & Environmental Science*, 8(1), 158-168.
- EEA. (2015). Monitoring CO₂ emissions from new passenger cars and vans in 2014. EEA Technical report No 16/2015: European Environment Agency.
- Egede, P., Dettmer, T., Herrmann, C., & Kara, S. (2015). Life Cycle Assessment of Electric Vehicles – A Framework to Consider Influencing Factors. *Procedia CIRP*, 29, 233-238.
- Elwert, T., Goldmann D, Römer, F., Buchert, M., Merz, C., Schueler, D., & Sutter, J. (2016). Current Developments and Challenges in the Recycling of Key Components of (Hybrid) Electric Vehicles. *Recycling*, 1(1), 25-60.
- Eriksson, O., & Finnveden, G. (2009). Plastic waste as a fuel - CO₂ neutral or not? *Energy & Environmental Science*, 2(9), 907-914.
- Ermolaeva, N. S., Castro, M. B. G., & Kandachar, P. V. (2004). Materials selection for an automotive structure by integrating structural optimization with environmental impact assessment. *Materials & Design*, 25(8), 689-698.
- Ernzer, M., & Birkhofer, H. (2002). *Selecting methods for life cycle design based on the needs of a company*. Paper presented at the Design 2002, The Design Society, Dubrovnik.
- European Commission-Joint Research Centre-Institute for Environment and Sustainability. (2010). International Reference Life Cycle Data System (ILCD) Handbook -General guide for Life Cycle Assessment -Detailed guidance Luxembourg: Publications Office of the European Union.
- European Commission. (2013). EU Transport in Figures 2013. Luxembourg.
- European Commission. (2014). Report on Critical Raw Materials for the EU.
- Farag, M. M. (2014). Quantitative Methods of Materials Selection *Mechanical Engineers' Handbook*: John Wiley & Sons, Inc.
- Faria, R., Marques, P., Moura, P., Freire, F., Delgado, J., & de Almeida, A. T. (2013). Impact of the electricity mix and use profile in the life-cycle assessment of electric vehicles. *Renewable and Sustainable Energy Reviews*, 24, 271-287.
- Fiksel, J. (2011). *Design for the Environment: A Guide to Sustainable Product Development* (Second ed.). USA: McGraw-Hill.
- Fink, A. (2010). *Conducting research literature reviews : from the Internet to paper* (Third ed.). London: SAGE.
- Finnveden, G., Hauschild, M. Z., Ekvall, T., Guinee, J., Heijungs, R., Hellweg, S.,...Suh, S. (2009). Recent developments in Life Cycle Assessment. *Journal of Environmental Management*, 91(1), 1-21.
- Frischknecht R., Jungbluth N., Althaus Hans-Jörg, Bauer Christian, Doka Gabor, Dones Roberto,... Nemecek Thomas. (2007). Implementation of Life Cycle Impact Assessment Methods Duebendorf, CH.
- Gillham, B. (2005). *Research interviewing: the range of techniques*. Maidenhead, UK: Open University Press.
- Giudice, F., La Rosa, G., & Risitano, A. (2005). Materials selection in the Life-Cycle Design process: a method to integrate mechanical and environmental performances in optimal choice. *Materials & Design*, 26(1), 9-20.
- Graedel, T. E. (1998). *Streamlined life-cycle assessment*. Upper Saddle River, NJ: Prentice Hall ; London : Prentice-Hall International.
- Granta Design. (2013). Granta CES Selector. Retrieved November 2013, From: <http://www.grantadesign.com/>

- Hallstedt, S. (2008). *A foundation for sustainable product development* (Doctoral thesis), Blekinge University of Technology, Karlskrona, Sweden.
- Hallstedt, S. I., Thompson, A. W., & Lindahl, P. (2013). Key elements for implementing a strategic sustainability perspective in the product innovation process. *Journal of Cleaner Production*, 51, 277-288.
- Handfield, R. B., Melnyk, S. A., Calantone, R. J., & Curkovic, S. (2001). Integrating environmental concerns into the design process: The gap between theory and practice. *Ieee Transactions on Engineering Management*, 48(2), 189-208.
- Hawkins, T. R., Gausen, O. M., & Strømman, A. H. (2012). Environmental impacts of hybrid and electric vehicles—a review. *The International Journal of Life Cycle Assessment*, 17(8), 997-1014.
- Hawkins, T. R., Singh, B., Majeau-Bettez, G., & Stromman, A. H. (2013). Comparative environmental life cycle assessment of conventional and electric vehicles. *Journal of Industrial Ecology*, 17(1), 158-160.
- Hedlund-Åström, A. (2005). *Model for End of Life Treatment of Polymer Composite Materials*. (Doctoral thesis), KTH, Royal Institute of Technology, Stockholm, Sweden.
- Hochschorner, E., & Finnveden, G. (2003). Evaluation of two simplified life cycle assessment methods. *International Journal of Life Cycle Assessment*, 8(3), 119-128.
- Holmberg, J. (1998). Backcasting: A natural step when making sustainable development operational for companies. *Greener Management International*, 23, 30-51.
- Howarth, J., Mareddy, S. S. R., & Mativenga, P. T. (2014). Energy intensity and environmental analysis of mechanical recycling of carbon fibre composite. *Journal of Cleaner Production*, 81, 46-50.
- Huijbregts, M. A. J., Hellweg, S., Frischknecht, R., Hendriks, H. W. M., Hungerbühler, K., & Hendriks, A. J. (2010). Cumulative Energy Demand As Predictor for the Environmental Burden of Commodity Production. *Environmental Science & Technology*, 44(6), 2189-2196.
- ICCT. (2014). Policy update: EU CO₂ Emissions standards for passenger cars and light duty commercial vehicles International council on clean transportation.
- IEA. (2015). Key World Energy Statistics. International Energy Agency.
- IPCC. (2007). Climate Change 2007: The Physical Science Basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change [Solomon, S., D. Qin, M. Manning, Z. Chen, M. Marquis, K.B. Averyt, M. Tignor and H.L. Miller (eds.)]. NY, USA.
- ISO 14006. (2011). Environmental management systems - Guidelines for incorporating ecodesign. International Organization for Standardization.
- ISO 14040. (2006). Environmental management - Life cycle assessment - Principles and framework: International Organization for Standardization.
- ISO 14044. (2006). Environmental management - Life cycle assessment - Requirements and guidelines: International Organization for Standardization.
- ISO TR/14062. (2002). Environmental management-Integrating environmental aspects into product design and development: International Organization for Standardization.
- Jerpdal, L., & Åkermo, M. (2014). Influence of fibre shrinkage and stretching on the mechanical properties of self-reinforced poly(ethylene terephthalate) composite. *Journal of Reinforced Plastics and Composites*, 33(17), 1644-1655.
- Johannesson, H., Persson, J. G., & Pettersson, D. (2013). *Produktutveckling : effektiva metoder för konstruktion och design (In Swedish)* (Second ed.). Stockholm: Liber.

- Johansson, G. (2002). Success factors for integration of ecodesign in product development: A review of state of the art. *Environmental Management and Health*, 13(1), 98-107.
- Johansson, G., Greif, A., & Fleischer, G. (2007). Managing the design/environment interface: studies of integration mechanisms. *International Journal of Production Research*, 45(18-19), 4041-4055.
- Jönbrink, A.-K., Kristinsdottir, A. R., Johansson, E., Nyström, B., Sundgren, M., & Nayström, P. (2013). Ekolyftet, en förstudie. Hinder och möjligheter i företags arbete med hållbarhet i sin produktframtagning (In Swedish) Swerea IVF-AB.
- Kara, S., Ibbotson, S., & Kayis, B. (2014). Sustainable product development in practice: an international survey. *Journal of Manufacturing Technology Management*, 25(6), 848-872.
- Kim, H.-J., McMillan, C., Keoleian, G. A., & Skerlos, S. J. (2010). Greenhouse Gas Emissions Payback for Lightweighted Vehicles Using Aluminum and High-Strength Steel. *Journal of Industrial Ecology*, 14(6), 929-946.
- Kmetty, A., Barany, T., & Karger-Kocsis, J. (2010). Self-reinforced polymeric materials: A review. *Progress in Polymer Science*, 35(10), 1288-1310.
- Knight, P., & Jenkins, J. O. (2009). Adopting and applying eco-design techniques: a practitioners perspective. *Journal of Cleaner Production*, 17(5), 549-558.
- Koffler, C. (2014). Life cycle assessment of automotive lightweighting through polymers under US boundary conditions. *The International Journal of Life Cycle Assessment*, 19(3), 538-545.
- Koffler, C., Krinke, S., Schebek, L., & Buchgeister, J. (2008). Volkswagen slimLCI: a procedure for streamlined inventory modelling within life cycle assessment of vehicles. *International Journal of Vehicle Design*, 46(2), 172-188.
- Kvale, S. (2009). *Interviews: An introduction to qualitative research interviewing*: SAGE Publications.
- La Rosa, A. D., Cozzo, G., Latteri, A., Recca, A., Björklund, A., Parrinello, E., & Cicala, G. (2013). Life cycle assessment of a novel hybrid glass-hemp/thermoset composite. *Journal of Cleaner Production*, 44, 69-76.
- La Rosa, D. A., Cozzo, G., Latteri, A., Mancini, G., Recca, A., & Cicala, G. (2013). A Comparative Life Cycle Assessment of a Composite Component for Automotive *Chemical Engineering Transactions*, 32, 1723-1728.
- Lewandowska, A., & Matuszak-Flejszman, A. (2014). Eco-design as a normative element of Environmental Management Systems—the context of the revised ISO 14001:2015. *The International Journal of Life Cycle Assessment*, 19(11), 1794-1798.
- Lewis, A. M., Kelly, J. C., & Keoleian, G. A. (2014). Vehicle lightweighting vs. electrification: Life cycle energy and GHG emissions results for diverse powertrain vehicles. *Applied Energy*, 126, 13-20.
- Lindahl, M. (2000). *Environmental Effect Analysis - An approach to Design for Environment* (Licentiate thesis), KTH, Royal Institute of Technology, Stockholm, Sweden.
- Lindahl, M. (2005). *Engineering Designers' Requirements on Design for Environment Methods and Tools*. (Doctoral thesis), KTH, Royal Institute of Technology, Stockholm, Sweden.
- Lindahl, M. (2006). Engineering designers' experience of design for environment methods and tools - Requirement definitions from an interview study. *Journal of Cleaner Production*, 14(5), 487-496.
- Lofthouse, V. (2006). Ecodesign tools for designers: defining the requirements. *Journal of Cleaner Production*, 14(15-16), 1386-1395.

- Luttropp, C., & Lagerstedt, J. (2006). EcoDesign and The Ten Golden Rules: generic advice for merging environmental aspects into product development. *Journal of Cleaner Production*, 14(15–16), 1396-1408.
- Lyu, M.-Y., & Choi, T. G. (2015). Research trends in polymer materials for use in lightweight vehicles. *International Journal of Precision Engineering and Manufacturing*, 16(1), 213-220.
- Ma, H., Balthasar, F., Tait, N., Riera-Palou, X., & Harrison, A. (2012). A new comparison between the life cycle greenhouse gas emissions of battery electric vehicles and internal combustion vehicles. *Energy Policy*, 44, 160-173.
- Majeau-Bettez, G., Hawkins, T. R., & Strømman, A. H. (2011). Life Cycle Environmental Assessment of Lithium-Ion and Nickel Metal Hydride Batteries for Plug-In Hybrid and Battery Electric Vehicles. *Environmental Science & Technology*, 45(10), 4548-4554.
- Messagie, M., Boureima, F. S., Coosemans, T., Macharis, C., & Van Mierlo, J. (2014). A Range-Based Vehicle Life Cycle Assessment Incorporating Variability in the Environmental Assessment of Different Vehicle Technologies and Fuels. *Energies*, 7(3), 1467-1482.
- Miles, M. B., & Huberman, A. M. (1994). *Qualitative data analysis : an expanded sourcebook* (Second ed.). London, UK: Sage.
- Millet, D., Bistagnino, L., Lanzavecchia, C., Camous, R., & Poldma, T. (2007). Does the potential of the use of LCA match the design team needs? *Journal of Cleaner Production*, 15(4), 335-346.
- Millet, D., Yvars, P.-A., & Tonnelier, P. (2012). A method for identifying the worst recycling case: Application on a range of vehicles in the automotive sector. *Resources, Conservation and Recycling*, 68, 1-13.
- Moberg, Å., Borggren, C., Ambell, C., Finnveden, G., Guldbbrandsson, F., Bondesson, A., . . . Bergmark, P. (2014). Simplifying a life cycle assessment of a mobile phone. *The International Journal of Life Cycle Assessment*, 19(5), 979-993.
- Moriarty, P., & Honnery, D. (2008). The prospects for global green car mobility. *Journal of Cleaner Production*, 16(16), 1717-1726.
- NHTSA. (2009). Average Fuel Economy Standards Passenger Cars and Light Trucks Model Year 2011. National Highway Traffic Safety Administration (NHTSA), US Department of Transportation (DOT).
- Nordelöf, A., Messagie, M., Tillman, A.-M., Ljunggren Söderman, M., & Van Mierlo, J. (2014). Environmental impacts of hybrid, plug-in hybrid, and battery electric vehicles—what can we learn from life cycle assessment? *The International Journal of Life Cycle Assessment*, 19(11), 1866-1890.
- O'Hare, J., Dekoninck, E., McMahon, C., & Turnbull, A. (2010). Adapting innovation tools to the eco-innovation requirements of industry: case study results. *International Journal of Design Engineering*, 3(2), 172-194.
- OECD-IEA. (2016). Global EV outlook 2015 Available at http://www.iea.org/evi/Global-EV-Outlook-2015-Update_1page.pdf.
- OECD/IEA. (2013). Global EV Outlook. Understanding the Electric Vehicle Landscape to 2020.
- Olson, E. M., Cooper, R., & Slater, S. F. (1998). Design strategy and competitive advantage. *Business Horizons*, 41(2), 55-61.
- OpenLCA. (2016). OpenLCA Retrieved August, 2016, from <http://www.openlca.org/>
- Pahl, G., Beitz, W., Feldhusen, J., & Grote, K.-H. (2007). Product Development Process *Engineering Design: A Systematic Approach* (pp. 125-143). London, UK: Springer London.

- Pigosso, D. C. A., McAlloone, T. C., & Rozenfeld, H. (2015). Characterization of the State-of-the-art and Identification of Main Trends for Ecodesign Tools and Methods: Classifying Three Decades of Research and Implementation. *Journal of the Indian Institute of Science*, 95(4), 405-427.
- Pigosso, D. C. A., Rozenfeld, H., & McAlloone, T. C. (2013). Ecodesign maturity model: a management framework to support ecodesign implementation into manufacturing companies. *Journal of Cleaner Production*, 59(0), 160-173.
- Pimenta, S., & Pinho, S. T. (2011). Recycling carbon fibre reinforced polymers for structural applications: Technology review and market outlook. *Waste Management*, 31(2), 378-392.
- Porter, M. E., & van der Linde, C. (1995). Green and Competitive - Ending the Stalemate. *Harvard Business Review*, 73(5), 120-134.
- Poulidikidou, S. (2012). A literature review on methods and tools for environmentally friendly product design and development. Identification of relevance to the vehicle design context (Report) KTH, Royal Institute of Technology, Stockholm, Sweden
- PRé Consultants. (2010). SimaPro 7 Developer
- Rebitzer, G., Ekvall, T., Frischknecht, R., Hunkeler, D., Norris, G., Rydberg, T., . . . Pennington, D. W. (2004). Life cycle assessment: Part 1: Framework, goal and scope definition, inventory analysis, and applications. *Environment International*, 30(5), 701-720.
- Regulation (EC) No 443/2009. (2009). Regulation (EC) No 443/2009 of the European Parliament and of the Council of 23 April 2009 setting emission performance standards for new passenger cars as part of the Community's integrated approach to reduce CO2 emissions from light-duty vehicles. (L140/1).
- Regulation (EC) No 1907/2006 of the European Parliament and of the Council of 18 December 2006 concerning the Registration, Evaluation, Authorisation and Restriction of Chemicals (REACH), establishing a European Chemicals Agency, amending Directive 1999/45/EC and repealing Council Regulation (EEC) No 793/93 and Commission Regulation (EC) No 1488/94 as well as Council Directive 76/769/EEC and Commission Directives 91/155/EEC, 93/67/EEC, 93/105/EC and 2000/21/EC (2006).
- Ribeiro, I., Peças, P., & Henriques, E. (2013). A life cycle framework to support materials selection for Ecodesign: A case study on biodegradable polymers. *Materials & Design*, 51, 300-308.
- Ritzén, S. (2000). *Integration environmental aspects into product development: proactive measures*. (Doctoral thesis), KTH, Royal Institute of Technology, Stockholm Sweden.
- Ritzen, S., & Lindahl, M. (2001). *Selection and implementation - key activities to successful use of EcoDesign tools*. Paper presented at the Second International Symposium on Environmentally Conscious Design and Inverse Manufacturing, EcoDesign 2001.
- Rossi, M., Germani, M., & Zamagni, A. (2016). Review of ecodesign methods and tools. Barriers and strategies for an effective implementation in industrial companies. *Journal of Cleaner Production*, 129, 361-373.
- Samaras, C., & Meisterling, K. (2008). Life Cycle Assessment of Greenhouse Gas Emissions from Plug-in Hybrid Vehicles: Implications for Policy. *Environmental Science & Technology*, 42(9), 3170-3176.
- Schneider, C. (2015). *Recyclable self-reinforced ductile fiber composite materials for structural applications*. (Doctoral thesis), KTH, Royal Institute of Technology, Stockholm, Sweden.

- Schneider, C., Kazemahvazi, S., Åkermo, M., & Zenkert, D. (2013). Compression and tensile properties of self-reinforced poly(ethylene terephthalate)-composites. *Polymer Testing*, 32(2), 221-230.
- Schögl, J. P., Baumgartner, R., & Hofer, D. (2014, May 19-23). *A checklist for sustainable product development: Improving sustainability performance in early phases of product design*. Paper presented at the The Tenth International Symposium on Tools and Methods of Competitive Engineering (TMCE 2014), Budapest, Hungary.
- Short, T., Lee-Mortimer, A., Luttrupp, C., & Johansson, G. (2012). Manufacturing, sustainability, ecodesign and risk: lessons learned from a study of Swedish and English companies. *Journal of Cleaner Production*, 37, 342-352.
- Simões, C. L., Costa Pinto, L. M., Simoes, R., & Bernardo, C. A. (2013). Integrating environmental and economic life cycle analysis in product development: a material selection case study. *The International Journal of Life Cycle Assessment*, 18(9), 1734-1746.
- Simões, C. L., Xará, S. M., & Bernardo, C. A. (2011). Influence of the impact assessment method on the conclusions of a LCA study. Application to the case of a part made with virgin and recycled HDPE. *Waste Management & Research*, 29(10), 1018-1026.
- Simon, M., Poole, S., Sweatman, A., Evans, S., Bhamra, T., & McAloone, T. (2000). Environmental priorities in strategic product development. *Business Strategy and the Environment*, 9(6), 367-377.
- SPE-14040-14. (2014). Life Cycle Assessment of Auto Parts - Guidelines for Conducting LCA of Auto Parts Incorporating Weight Changes Due to Material Composition, Manufacturing Technology, or Part Geometry: Canadian Standards Association (CSA Group).
- Stephan, C. H., & Sullivan, J. (2008). Environmental and Energy Implications of Plug-In Hybrid-Electric Vehicles. *Environmental Science & Technology*, 42(4), 1185-1190.
- Sullivan, J., Williams, R., Yester, S., Cobas-Flores, E., Chubbs, S. T., Hentges, S. G., & Pomper, S. D. (1998). *Life Cycle Inventory of a Generic U.S. Family Sedan Overview of Results USCAR AMP Project*. Paper presented at the Total Life Cycle Conference & Exposition, Graz, Austria.
- Tate, E. D., Harpster, M. O., & Savagian, P. J. (2008). *The Electrification of the Automobile: From Conventional Hybrid, to Plug-in Hybrids, to Extended-Range Electric Vehicles*. Paper presented at the 2008 World Congress, April 14-17, Detroit, Michigan.
- thinkstep. (2015). GaBi software and databases for life cycle assessment.
- Thompson, A. W., Lindahl, P., Hallstedt, S., Ny, H., & Broman, G. (2011). *Decision Support Tools for Sustainability in Product Innovation in a Few Swedish Companies*. Paper presented at the International Conference on Research into Design (ICoRD), Bangalore.
- Tingström, J. (2007). *Product Development with a Focus on Integration of Environmental Aspects*. (Doctoral thesis), KTH, Royal Institute of Technology, Stockholm, Sweden.
- Tingström, J., & Karlsson, R. (2006). The relationship between environmental analyses and the dialogue process in product development. *Journal of Cleaner Production*, 14(15-16), 1409-1419.
- Tingström, J., Swanström, L., & Karlsson, R. (2006). Sustainability management in product development projects – the ABB experience. *Journal of Cleaner Production*, 14(15-16), 1377-1385.
- Tukker, A. (2014). Rare Earth Elements Supply Restrictions: Market Failures, Not Scarcity, Hamper Their Current Use in High-Tech Applications. *Environmental Science & Technology*, 48(17), 9973-9974.

- Tukker, A., Eder, Charter, M., Haag, E., Vercalsteren, A., & Wiedmann, T. (2001). Eco-design: The State of Implementation in Europe – Conclusions of a State of the Art Study for IPTS. *The Journal of Sustainable Product Design*, 1(3), 147-161.
- Tyl, B., Legardeur, J., Millet, D., & Vallet, F. (2014). A comparative study of ideation mechanisms used in eco-innovation tools. *Journal of Engineering Design*, 25(10-12), 325-345.
- Ulrich, K. T., & Eppinger, S. D. (2008). *Product design and development* (Fourth ed.). New York, USA: McGraw-Hill Higher Education.
- Vallet, F., Eynard, B., Millet, D., Mahut, S. G., Tyl, B., & Bertoluci, G. (2013). Using eco-design tools: An overview of experts' practices. *Design Studies*, 34(3), 345-377.
- Whitney, D. E. (1990). Designing the design proces. *Research in Engineering Design*, 2, 3-13.
- Witik, R. A., Payet, J., Michaud, V., Ludwig, C., & Månson, J.-A. E. (2011). Assessing the life cycle costs and environmental performance of lightweight materials in automobile applications. *Composites Part A: Applied Science and Manufacturing*, 42(11), 1694-1709.
- Witik, R. A., Teuscher, R., Michaud, V., Ludwig, C., & Månson, J.-A. E. (2013). Carbon fibre reinforced composite waste: An environmental assessment of recycling, energy recovery and landfilling. *Composites Part A: Applied Science and Manufacturing*, 49, 89-99.
- Wohlecker, R., Johannaber, M., & Espig, M. (2007). *Determination of Weight Elasticity of Fuel Economy for ICE, Hybrid and Fuel Cell Vehicles*. SAE Technical Paper
- Yang, Y., Boom, R., Irion, B., van Heerden, D.-J., Kuiper, P., & de Wit, H. (2012). Recycling of composite materials. *Chemical Engineering and Processing: Process Intensification*, 51, 53-68.
- Yin, R. K. (2009). *Case study research: design and methods* (Fourth ed.). London, UK: SAGE.
- Yin, R. K. (2012). *Applications of case study research* (Third ed.). London, UK: SAGE.
- Åström, B. T. (1997). *Manufacturing of Polymer Composites*. Cheltenham, UK: Nelson Thornes Ltd.

Appendix: Interviews protocol used for Paper I

COMPANY:

PRODUCT:

RESPONDENT:

ROLE AND EXPERTISE:

DEPARTMENT:

A. Introduction

A brief introduction to the purpose of the study is given by the interviewer. There is time for questions and clarifications in relation to the interview process.

B. Opening questions

- Could you please describe your background and role in the company?
- Could you mention a few words about your department in relation to the structure of the company and product development process?
- How is your role affecting the product design and development process and specifically when the environmental performance of the product is concerned?
- Could you describe the environmental policy of your company in general? Are there specific strategies/goals concerning environmental issues? Which department/s is/are responsible for working with environmental issues in the company?

C. Product design and development

- Could you shortly describe the product design and development process (e.g. the major steps, time frames, specializations and people involved)?
- Do you use any type of method/tool in the product design stage (e.g. CAD tools)?
- What are the main aspects to consider during the design process related to the product?
- To what extent are product's specifications defined by the company/customer/regulation?

D. Environmental aspects and eco-design

- What are the major environmental challenges that your company need to consider in relation to the product and in a life cycle perspective?
- What is the motivation for the company to improve the environmental performance of the products (consumer demand, legislation, cost reduction etc.)?
- What strategies are adopted to cope with these challenges and improve the environmental performance of your product?
- To what extent are these challenges considered at the product development stages?
- How are requirements in relation to the major environmental constrains identified?

- What processes for integrating environmental aspects during product development are followed?
- How difficult/easy/ successful or not is to balance environmental requirements to the other design requirements that need to be considered in relation to the product?

E. Use and experience on DfE/eco-design tools

- Are you familiar with/have experience on using any type of eco-design tools? Are any of these tools systematically applied in the company?
- Why are tools used? (if any)
- Have you experience in developing/using ecodesign guidelines?
- What types of environmental impact assessment methods or tools are you using?
- Who is responsible for performing environmental assessments?
- How are results of these studies communicated /integrated to the product development process and design decisions?
- What potentials or barriers do you see regarding the tools you are using?
- What are your general requirements on ecodesign/impact assessment tools? Are there any formal requirements?
- Who decides about the methods and tools that are to be used? Are there any criteria?
- How often do you meet trade-off situations? How do you usually handle them? (E.g. among different environmental aspects or environmental and other aspects)? Are tools supporting such process?
- Do you have/use any database (internally or sector based) with information about your products? Like for example: raw materials composition, energy needs per product, emissions, toxicity etc.
- In case that no assessment method is used, were there any previous attempts to apply and use such tools? What were the main reasons/identified difficulties preventing their use?

F. General questions

- Is any environmental management scheme under implementation? E.g. EMAS, ISO 14000 etc.? Do you publish environmental/sustainability reports?
- Is there education and training of the employees regarding environmental issues?
- Is there education/training about the assessment methods and tools?
- Did you attend any internal seminars regarding environmental issues?
- Do you set specific demands to your suppliers related to their environmental performance? Are they prepared to provide specific information to the companies if needed (e.g. material/substance composition of their products)?