Eco-design tools within product development processes of automotive companies and lessons learned from their experience

BMW, Volkswagen and Volvo: a comparative study

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Abstract

Over the past years, the scientific community has payed increasing attention to the integration of Eco-design in product development processes. In spite of this, Eco-design practices within mainstream manufacturing companies has proven to be scarce. A great share of the literature has focused on the development and improvement of Eco-design tools from a theoretical perspective. A more practical perspective, including companies' point of view, allow us to identify bottlenecks or improvement potential only visible for practitioners, such as the compatibility of tools with companies' current procedures, time and data constraints, or guidance provided by output mechanisms. This thesis reviews a set of Eco-design tools adopted or developed by three automotive companies (BMW AG, VW AG and AB Volvo) with decades of experience in Eco-design. The extensive literature review aims at combining and integrating the observed best practices into a model that offers guidance on how to incorporate Eco-design into product development processes of less experienced companies. The model presents an iterative process comprised of three phases: impact assessment, definition of action, and management and control. The impact assessment phase consists of the analysis of hotspots and the comparison of design alternatives. The results from the impact assessment then lead to the definition of improvement actions. Actions that are agreed through team dialogues among different departments of the company which are selected according to a prioritization process to find the right balance between aspects, such as costs, product functionality, customer preference, current and future policy compliance or corporative image. Once impact results are translated into technical targets, the management and control phase ensures that employees are designated to supervise the implementation of actions, report possible rebound effects and inform about the findings that become the knowledge foundation of future projects. The automotive experience also reveals that LCA represents the cornerstone of the three companies in the integration of Eco-design practices, but it is noteworthy that LCA approaches are recognized to be dependent on other indispensable tools. From the observed experience, the LCA studies are conducted in a form that are too dependent on the product system of preceding versions of the product, which often limits radical innovation and rather results in small incremental improvement. In combination with LCA, systematic team dialogues between different knowledge fields shall contribute to the creation of collective knowledge. An appropriate arena that allows experts to reflect on impact results and explore innovative improvement opportunities, out of the scope of LCA practitioners.

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Acronyms

CAD	Computer-aided design
CML	Institute of Environmental Sciences of Leiden
DfX	Design for X Approach
EC	Environmental Commendation
EEA	Environmental Effect Analysis
EIA	Environmental Impact Analysis
ELU	Environmental Load Unit
EMS	Environmental Management System
EoL	End of Life
EPS	Environmental Priority Strategies
E-FMEA	Environmental Failure Mode Effect Analysis
ISO	International Organization for Standardization
LCA	Life Cycle Assessment
LCC	Life Cycle Cost
LCE	Life Cycle Engineering
LCSA	Life Cycle Sustainability Assessment
PSB	Product Sustainability Budget
S-LCA	Social Life Cycle Assessment
SHDB	Social Hotspot Database

Executive Summary

The environmental damage caused by consumer products are determined by the environmental flows associated with its life cycle. A life cycle that begins with the design of the product, where designers decide on material, functionality and process planning. These decisions highly influence the environmental performance of the following life cycle stages, and as a product progresses through these stages, the ability to reduce the environmental impacts of each stage decreases. This demonstrates the importance of including environmental considerations in early design phases, a practice that is so far perceived as scarce in the majority of mainstream industries.

This thesis presents a review of a set of Eco-design tools adopted by three car manufacturers (BMW, VW and Volvo), with the purpose of extracting best practices and proposing guidelines to help other companies in the implementation of Eco-design practices. The methodological framework used in this thesis is developed to be repeatable by future researchers on the Eco-design experience of alternative sectors.

Companies' strategies showed partial visions of how to proceed in the implementation of Eco-design and in order to present a more complete picture on this, this thesis presents a new Eco-design model based on the combination of best practices. The proposed model recommends companies to implement Eco-design through an iterative process comprised of three phases, in which the selected tools must fulfil the following often overlooked requirements:

(1) Impact Assessment: (i) Identify impact hotspots and compare alternative designs in a scientifically rigorous manner (in accordance with ISO 14000/44); (ii) Systematic interpretation of LCA results that allow engineers and designers to consult impacts of their decisions; (iii) The speed of the impact assessment must be in line with the timeframe set by the product development process.

(2) Definition of Action: (i) Capacity to share information among different knowledge fields that allows to create collective knowledge and agree upon improvement actions; (ii) Prioritize improvement actions balancing multiple criteria including costs, willingness-to-pay of customers, functionality aspects, and current and future legislation; (iii) Translate improvement actions into measurable technical targets, using a language that is familiar for designers and engineers.

(3) Management & Control: (i) Designate employees for the supervision of the implementation of improvements; (ii) Share and monitor the arising obstacles; (iii) Evaluate the results of the improvement actions to identify possible rebound effects; (iv) Findings of the Eco-design implementation shall be reported to conform the knowledge foundation of future projects.

The experience of the three companies emphasizes the key role played by LCA in the implementation of Eco-design, but also remarks its incapacity to address this challenge alone.

Every company has adopted or developed a method (PSB at BMW, LCE at VW and EIA at Volvo) that assists in the interpretation of LCA results and the definition of action based upon them. This observation stresses companies' demand for tools that allow experts to reflect on impact results and enable them to explore improvement opportunities out of the LCA scope. From the observed experience, the LCA studies are conducted in a form that are too dependent on the product system of preceding versions of the product, which often limits radical innovation and rather results in small incremental improvement. In combination with LCA, systematic team dialogues between different knowledge fields shall contribute to the creation of collective knowledge. An appropriate arena that allows experts to reflect on impact results and explore innovative improvement opportunities, out of the scope of LCA practitioners.

Chapter 1: Introduction

1.1. Context

Human activities are increasingly influencing the climate and the earth's temperature, mainly by burning fossil fuels, cutting down rainforests and farming livestock (European Commission, 2019). These activities affect four of the nine systems responsible to regulate the resilience of the Earth system, posing a risk for the current and future societies (McGill University, 2015). Over the last decade, factors such as the consensus in the scientific community regarding the causes of Global Warming, the adoption of Multilateral International Agreements and the perceived impacts of Climate Change, have raised environmental awareness among the different levels of society. Consumers start to demand more environmentally friendly products to adopt more sustainable life-styles and producers try to use cleaner production alternatives to meet their emission targets (Schmeltz, 2012, Frondel et al., 2015).

Environmental emissions of products are determined by environmental emissions associated with the life cycle, which includes resource extraction, manufacturing, distribution and end-of-life stages. As a product progresses through its life cycle, the ability to reduce the environmental impacts of each stage decreases (Nasr, 2019). Meaning that environmental consequences of a stage are highly influenced by decisions taken in earlier stages of its life cycle. Product design can be considered the beginning of the life cycle. A great part of sustainability characteristics of a product are determined in the early design phase, where product designers have to make decisions in areas such as material selection, functionality and process planning. These decisions highly influence the environmental performance of the following life cycle stages (Chiu & Chu, 2012).

Eco-design tool is a method or a combination of methods that allows the assessment of the environmental performance of different product or service alternatives, and/or that provide guidance for strategies to improve this performance. This tool allows designers to include environmental considerations into product design phases, in order to minimize life cycle environmental impacts (Brezet and van Hemel 1997, Lifset and Graedel 2002). This way environmental considerations can support the decision-making of product designers, by balancing them against other traditional requirements such as costs, features and consumer preferences. In order to assess these impacts a life cycle approach is crucial. Eco-design tools often integrate life cycle assessment (LCA) (UNEP/SETAC 2012; Remmen et al. 2007; de Pauw et al. 2014). Life Cycle Assessment (LCA) is a method that allows to assess the environmental performance of products or services over their entire life cycle. A life cycle approach, which considers the entire life cycle is essential to avoid burden shifting, in order to ensure that reducing the environmental impact at one stage in the life cycle does not cause an unforeseen increase in another stage.

Karlsson and Luttropp (2006) stated that, to foster sustainable development, Eco-design tools should be made available for companies and should serve to clarify relations between design and environmental considerations. A number of studies have demonstrated the applicability of Eco-design tools. Unfortunately, integration of Eco-design tools in product development processes has proven to be scarce (Bovea et al., 2012). Pigosso et al. (2013) says this is mainly due to difficulties in Eco-design implementation and management. Frick and Laugen (2012) on the other hand, stated that these tools are developed for experts and they are not adapted to designer's needs, knowledge, tools and practices. They are often too complex and data intensive, or they lack guidance on how to define and prioritize the eco-design practices to be implemented (Frick and Laugen, 2012).

Considering environmental impacts from the early design phase of a product, is crucial to move towards cleaner production and sustainable consumption practices. This emphasizes the role of designers and thus the importance to provide them with reliable environmental knowledge to support and guide their decisions. Eco-design tools have the potential to inform companies about the consequences of their actions from an environmental perspective. However, their implementation is still scarce. According to Bovea et al (2012), despite the wide variety of tools available, the case studies presented are, in many cases, theoretical examples, without the participation of a manufacturing company. This thesis helps to have an overview of various Eco-design tools utilized and created by manufacturing companies, with the purpose of learning how they have successfully integrated these tools in their design processes.

1.2. What is an Eco-design tool?

Eco-design is defined as the integration of environmental aspects into product design and development with the aim of reducing negative environmental impacts throughout a product's life cycle (ISO 14006, 2011). As defined in the standard, the Eco-design process consists of six phases: (1) Specify product functions; (2) Environmental assessment of products; (3) Strategies of improvement; (4) Environmental objectives; (5) Product specification; and (6) Technical solutions.

In line with this definition Pigosso et al. (2013) classified Eco-design practices into two main groups: management practices and operational practices. Management practices refer to practices aimed at managing the product development and related processes, while operational practices are related to technical product design specifications. According to this author, management practices include (1) phases of the product development process (i.e. clearly define goals to improve products environmental performance), (2) support processes (i.e. make Eco-design tasks a part of the daily routine for the relevant employees) and (3) generic activities (i.e. clearly define the environmental indicators and the methodology to be used during the environmental assessment phase). On the other hand, operational practices are grouped into six strategies: minimize energy consumption, minimize material consumption, extend material life span, optimize product life span, select low impact resources and processes; and facilitate disassembly.

The Eco-design tool can be defined as the systematic approach to support the application of both Eco-design management and operational practices. Rossi et al. (2016) classified Eco-design tools in the following categories: Life Cycle Assessment (LCA), Simplified LCA, CAD integrated tools, Diagram tools, Check list & Guidelines and Design for X approach. Although it is debatable whether LCA should be considered as an Eco-design tool. It is certainly true that LCA can support Eco-design, as it is shown in Navajas et al. (2017), but its potential goes beyond Eco-design. For instance, from a governance approach LCA is able to support the evaluation, formulation and implementation of policies, whereas in industry the method can support marketing purposes (e.g. Eco-labelling) and selection of suppliers (Owsianiak et al., 2018). In recognition of this fact, LCA will be considered from now on an Eco-design tool, as this thesis focuses on the tool's ability to support Eco-design practices mentioned above. Therefore, the rest of possible applications connected to LCA are out of the scope of this thesis.

As it is explained in section 1.3, most of the Eco-design literature paid much attention to the study of generic Eco-design tools. 'Generic tools' refer to tools that are not focused on a particular sector, and thus they are intended to be used among all sectors. Few of these studies have analysed how a particular industry has adapted generic tools and have integrated them in their product development processes.

1.3. Literature review and scientific gap

The topic of Eco-design tools has been extensively studied by the Eco-design research community. In recent years, several authors conducted studies analysing the drivers of the slow take-up of Eco-design tools in industry, by conducting survey and interview analysis of experts in the field. Bey et. al. (2013) stated that lack of information on environmental impacts and lack of expert knowledge are the main barriers companies have to face. This study suggested that the utilization of environmental support tools can improve the information flow and they can facilitate sharing potentially existing knowledge within the company. A similar study also states that design tools are likely to be used in the medium-and high complexity product development by manufacturers in order to enhance Eco-design practices (Kara et al., 2014). Dekoninck et al. (2016) presented the most comprehensive study in this field, by classifying the challenges into five major areas: strategy, tools, collaboration, management and knowledge.

Besides the identification of barriers and challenges, in the literature we can also find studies presenting methods to overcome them. Pigosso et al. (2013) for their part developed a management framework to support companies in the process of Eco-design implementation. The framework allows companies to evaluate their Eco-design maturity profile, understand improvement opportunities and select Eco-design practices. More recent research presented a framework of techniques and methods to identify opportunities where information from downstream stages can enable more accurate decisions in early design phases (Brundage et al., 2018).

Lofthouse (2006) contributed to the field of Eco-design by presenting the requirements that industrial designers have of Eco-design tools. According to her findings, these tools should be based on a combination of guidance, education and information, along with reliable content, appropriate presentation and easy access. Additionally, some years later Birch et al. (2012) contributed in this area with his work which consisted in analysing the usefulness of the output mechanisms of 22 Eco-design tools from the designer’s point of view. The analysis revealed that in the majority of tools the resulting guidance is strategy focused and generic, and thus of limited use to designers. These tools indicate which processes cause higher environmental impacts but fail to demonstrate how to solve this in a product specific way.

As mentioned before in the introduction, Bovea et al. (2012) claimed that many of the case studies presented in the literature miss to involve manufacturing companies. Fitzgerald et al. (2007) suggest that tools, such as guidelines and checklists, need to be company-specific and integrated systematically in the product development process, and that using standalone and generic tools may not be effective. In this respect, Wrisberg et al. (2012) adds that a successful use of environmental tools in a company's decision procedure requires the adaptation and customisation of tools (Wrisberg et al., 2012). Companies must adapt the tools according to their culture, specific product development process and their current tools (Quella and Schmidt, 2003). In this regard, few studies have addressed the integration of Eco-design tools in manufacturing companies by analysing their application in real-world processes. Examples of these studies are addressed in the following paragraphs, in the context of the automotive industry.

The automotive industry has received special attention due to its years of experience in the field of Eco-design. Poulikidou et al. (2014) studied the integration of Eco-design practices into four Swedish vehicle manufacturing companies. This helped to gain insights into how Eco-design is functioning and thus proposes guidelines to move forward. Recommendations include enhancing the communication of the processes regarding these tools, as well as their potential to improve products ecological profile. In line with this recommendation and to enhance the understanding of Eco-design tool’s processes and their integration into companies’ operations, this thesis deepens the subject addressed by two studies: Chanaron (2007) and Garcia et al. (2012). These studies are essential for this thesis, as their contribution serves as the knowledge foundation in which it is built upon.

Chanaron (2007) reviewed the main Eco-design tools used by the mainstream car maker corporations. This study serves to have a quick overview of their Eco-design methods, emphasizing mainly on their applications and achievement until 2007. After this enormous contribution, the study brought up unanswered questions regarding the interaction of different Eco-design tools. Chanaron (2007) observed that every company has several tools working together and every one of them serves a specific function. However, this study misses to address these interactions. Garcia et al. (2012) explored this field by identifying the role of these Eco-design tools within the overarching environmental strategy of three automotive companies (VW, Ford, Volvo). These observations lead to the development of an ideal model of strategy that guides companies in the selection of the right combination of methods. This model proposes how information should flow throughout three layers of knowledge (research, development and innovation), and which type of tools are to be used in every layer to manage this information. Garcia et al. (2012) helped to understand how a right selection of Eco-design tools can work together and interact to pursue an overarching goal. For this, the author used a holistic approach where Eco-design tools behaved as the elements that conform the structure of a system of tools. In that study, Eco-design tools were analysed as black-box systems by examining their functional application without considering their internal structures or workings. In contrast with Garcia et al. (2012), this thesis intends to have a deeper look into the mechanisms that govern these tools.

In conclusion, Chanaron (2007) and Garcia et al. (2012) studied what Eco-design tools do in automotive companies, their outcome, while this thesis wants to address how they produce these outcomes. For that, this thesis further examines the functioning of the elements (Eco-design tools) that make up the system of tools, getting a deeper understanding of their goal, scope, required resources, sustainability coverage, operationalization and participants. The systematic comparison of tools provides a comprehensive overview of the tools attributes, which enables us to identify the strengths and weaknesses of every tool, it serves to determine which case or context is more suitable for, and it allows us to observe how tools have been evolving throughout the years to adjust to new needs and obstacles. Additionally, this thesis also provides new insights by analysing the tools that have been developed since the mentioned studies were published.

1.4. Objectives and scope

Once the scientific gap is identified, the following chapter addresses the main objectives of this research and defines the main research question. It is necessary to clarify that the aim of this research is not to show the readers an absolute reality of the history of Eco-design tools in a particular sector. The real aim is to demonstrate that taking a systematic approach it is possible to learn from the experience of companies on the development and operationalization of Eco-design tools. For that, this thesis creates a framework that enables the systematic comparison of Eco-design tools within a given sector. In order to prove its applicability and the usefulness of its results, the framework is tested in a pilot environment where only public data sources are used. It is important to take into account that the results of this framework are influenced by the content of a limited amount of data sources, and thus they explore the matter from a particular perspective, which might not fully represent a complete picture of what occurs in automotive companies.

The developed framework has to facilitate the following actions: (1) Systematic comparison of the Eco-design tool's most relevant attributes, for the identification of similarities and highlights of differences among these attributes; (2) Identify strengths and weaknesses of the given tools; (3) extract lessons from the sector's experience on the development, utilization and evolution of these Eco-design tools.

In particular, this thesis is focused on the automotive sector due to its years of experience in this field. The automotive design is restricted by environmental regulations, mainly focusing on reducing emissions in the use phase (Perry et al., 2018). These regulations have contributed to the integration of Eco-design tools in this sector. An example of this is Groupe PSA's seven years of experience in life cycle methodology to make environmentally virtuous design choices (Perry et al., 2018). Another reason for choosing this sector is the fact that everyone knows what a vehicle is and what it is made for. Meaning that analysing tools that influence the design of such a well-known and tangent product facilitates the analysis of the actual tool.

In this thesis, a company specific approach serves to observe how generic Eco-design tools have been adapted to specific applications in a business environment. This helps to look at tools through concepts which companies are more familiar with, and thus increasing their interest towards our findings. Knowledge acquired from this thesis is meant to be relevant to stakeholders in sectors where Eco-design practices are yet not implemented, and knowledge acquired by the automotive sector's experience can be applied to their field. Therefore, lessons extracted from the automotive sector's experience have a generic nature, intended to be applicable for companies outside this sector.

According to the scientific gap and the main research goal, we define the following research question: ***How can we learn from the comparison of Eco-design tools utilized by automotive companies, regarding their development, utilization and evolution within product development processes?***

In conclusion, it is fair to say that the thesis revolves around the development of the comparative framework. This overarching goal is at the same time divided into a set of milestones that mark the roadmap to answer the research question: (1) collect and interpret scientific literature about the use of tools in companies, (2) connect the experiences reviewed to the theories around the evolution of LCA, (3) create a systematic model that describes the interaction of LCA with other tools to support Eco-design, based on the methods adopted by three automotive companies.

1.5. Research Approach & Sub-questions

As mentioned in the previous chapter, the main goal of the research is to develop a framework that analyzes Eco-design tools, with the purpose of extracting lessons from the automotive sector's experience on the development and evolution of these tools. For that, this thesis systematically compares a set of Eco-design tools adopted by the automotive sector in terms of goal, scope, required resources, sustainability coverage, operationalization and participants. Knowledge acquired from this comparison serves as a basis to learn how tools have been integrated, and have evolved throughout the years to adjust to new needs imposed by the new contexts in which they are used. This study conducts a systematic comparison of Eco-design tools through a qualitative approach and extracts lessons by interpreting the results of the comparison. The scientific articles or other sources supporting tools and methods for Eco-design in the automotive industry, of the last two decades, will be reviewed with the following purposes: (1) to define a screening criteria, that enables the systematic comparison of Eco-design tools in the automotive sector, and that serves to identify their shared attributes and to highlight their differences, (2) to conduct a screening of different tools, that enables to identify the strengths and weaknesses of every tool, and that allows to identify in which context they perform better (3) to study how tools evolve in time, identifying changes that their attributes suffer and interpreting the cause of these changes by observing the context in which they happened and (4) to define a systematic model able to guide companies to drive Eco-design practices, supported by the theories and interpretations derived from literature. The following are the sub-questions which will serve to build up the required knowledge to answer the main research question (sub-questions are divided into the three steps mentioned above):

1. What screening method allows the systematic comparison Eco-design tools’ relevant attributes?
2. What are the strengths and weaknesses of every Eco-design tool?
3. What changes in tool’s features over time can be identified from their comparison and what can be the cause of the identified changes?
4. Which pathway can companies follow to drive Eco-design practices assisted by tools?

Chapter 2: Methodology

The methodology to answer the first sub-question is based to a large extent on a standardized protocol to evaluate sustainability assessment tools proposed by Broeren et al. (2018). This method allows for a consistent and systematic examination of sustainability tools using a predetermined list of criteria. The protocol was designed to help organisations to select the most appropriate tools for given projects by identifying and balancing strengths and weaknesses (Broeren et al., 2018). By adapting the evaluation criteria proposed in this protocol, an adjusted screening method is developed that allows the evaluation of Eco-design tools in the automotive industry.

Due to the large number of Eco-design tools and for simplification purposes, this study focuses on a limited set of both quantitative and qualitative tools. For this selection of tools, firstly an expert consultation is carried out in combination with a review of published scientific literature on this matter. This leads to a pre-selection of Eco-design tools.

In a second step, these tools are reviewed thoroughly and some of these tools are discarded due to lack of data or other issues that are discussed later. This step is known as “Understanding the tools”. This process combines the search for aspects most tools share to enable their comparison, with the search of areas where they diverge to highlight their differences. The knowledge acquired in this process forms the basis to develop the criteria used in the screening method. Understanding the tools is essential before defining an evaluation criterion, since first it is necessary to comprehend the aspects that need to be evaluated.

The screening method serves to better examine the properties of the tools, as it allows us to compare their performance in a number of categories. This provides a visual way to identify the similarities and highlight the differences of the studied tools. Additionally, the results of the screening method also provide an intuitive framework to communicate the findings of the “understanding the tools” process in a summarized form.

To answer the second sub-question, once the screening criteria is developed, the screening is performed which results in the qualitative comparison of the tools in a table form. The results will describe the main characteristics of each tool, by providing concise information in terms of their goal, scope, required resources, sustainability coverage, operationalization and participants. The screening will lead to the discussion of similarities and differences among the tools.

The third phase of this thesis consists in interpreting the results from the screening to observe how tools have been integrated, and have evolved throughout the years to adjust to new needs and obstacles. For that, the author reflects on the screening to identify trends in Eco-design tools’ attributes, changes occurred during the evolution process, in areas such as goal, scope, required resources, sustainability coverage, operationalization and participants.

While observing these trends, it will be crucial to reflect on their context, in order to understand how every context calls for different kinds of tools and how these tools evolve or shift when the scenario around them changes.

In the final phase, the author reflects on the knowledge gained throughout the thesis, to conclude with a systematic procedure that can guide companies to drive Eco-design practices. To do so it is necessary to understand the potential and limitations of tools as isolated elements, in order to be able to build a theoretical system where they complement and interact with each other.

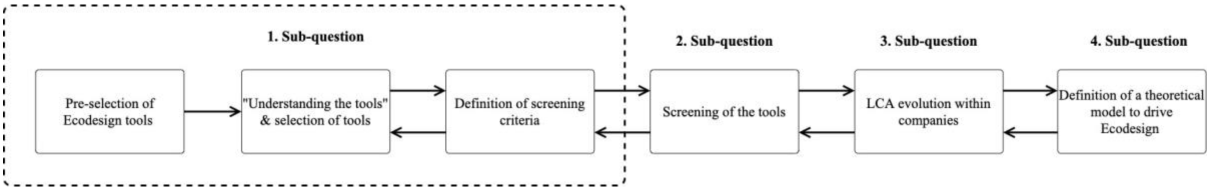


Figure 1. Flow diagram of the proposed framework to compare Eco-design tools within companies.

2.1 Pre-selection of tools

The thesis starts with the pre-selection of the Eco-design tools to be compared. According to Garcia et al. (2012), in the automotive sector the integration of the environmental dimension is achieved through the harmonization of Eco-design tools. Two main groups of tools can be identified: Diagnosis tools and Improvement tools. Diagnosis tools serve to assess the environmental performance of a decision, while improvement tools serve to produce guidelines to improve this performance. Every company has adopted diagnosis and improvement tools that interact by exchanging information and complementing each other as constituents of a bigger system of tools. This pre-selection process aims at identifying a number of Eco-design tools, clustered into the tool systems of different companies.

This pre-selection process combines a work of desk research with expert consultation. During the desk research, an extensive review of scientific literature is carried out to acquire knowledge about Eco-design tools in the automotive industry, including tools used by companies and tools with potential to be used by companies in the future. In this process, google scholar and science direct are the main search engines. This literature review is focused on peer-reviewed scientific articles containing the key-words ‘Eco-design’ or ‘Design-for-Environment (DfE)’, and ‘automotive’. This search results in a number of articles. Some of the articles are excluded based on their titles. The resulting number of articles is then reduced when the abstract shows that the article does not address the integration of Eco-design tools in the automotive industry. When the articles make it through this selection process, their content is reviewed to find relevant data. After these articles are reviewed, a snowball and pearl-growing search methods are combined to enhance the chances of finding additional relevant articles. The literature review results in a selection of a preliminary list of tools. This preliminary list of tools is later shared with experts in the field. This expert consultation aims at confirming the knowledge gained from the literature study and at providing new insights about additional methods used in industry.

Based on the desk research and the expert consultation, a list of Eco-design tools is selected. This selection aims at covering a wide variety of Eco-design tools to facilitate the comprehension of their different functions within an EMS. For this purpose, it is preferable to select tools that contain a level of uniqueness, a distinctive feature that makes them differ from the rest. This variety helps produce more fruitful insights, as allows to identify different strategies and to inform more clearly about the benefits and trade-offs of each tool compared to the others. It is acknowledged that an excessive homogeneity in the tools selected can compromise the quality of the results drawn from the comparison.

For their selection, these tools need to fulfil the following requirements. Firstly, the tool must have been integrated into the product development process of an automotive company or it must have been developed in collaboration or supervision of an automotive company. Furthermore, the tools have to fulfil at least one of the functions proposed by Millet et al (2003). According to this author and remarked by Garcia et al. (2012), every Eco-design tool should meet any of the following functions: Illustration for having a good picture of the environmental issue; diagnosis to identify the environmental hotspots of the reference product; definition of the objectives from the diagnosis; recommendation to find areas for improvement and evaluation/classification to make the best choices thanks to a multi-criteria analysis (cost, time, quality, environment …).

2.2 Understanding the tools & selection

The next step is based on the framework proposed by Broeren et. al. (2018). This step is known as 'Understanding the tools', and consists of collecting and classifying data related to each of the tools selected in the previous step. In order to check the availability of the needed data, a review of the data sources is conducted. Data sources vary from publications provided by the tool developers, to scientific articles, expert interviews or company's sustainable reports with relevant information about the tools. To find these data sources, google search engine is used. Keywords used for the search are the name of the tool and the corresponding name of the company (i.e. Life Cycle Sustainability Assessment BMW). Snowball and pearl-growing search methods are also used to enhance the chances of finding additional relevant data sources. When a source provides relevant data, this data is classified in the following categories: goal, scope, required resources, sustainability coverage, operationalization and participants. The categories are based on the framework proposed by Broeren et. al. (2018) and they are adjusted to fulfil the needs of this thesis. The search for sources for a single tool is completed when data from all the categories is gathered or when not more relevant data is found. To assess if the data provided by a source is enough, the following questions are asked:

Chapter 1: Goal:

1.1 What is the role of this tool in the company's sustainability strategy?
1.2 What is the question the tool aims to answer?
1.3 Has the tool already been used by the company? If yes, what was its application?

Chapter 2: Scope:

2.1 What is the scope of the tool within the company?
2.2 What is the tool's system boundary? Does it consider the entire life cycle of the product?
2.3 Does it have a functional unit? If yes, what is it?

Chapter 3: Required resources:

3.1 What is the time the company invests on the tool?
3.2 What is the data required? Where does the data come from? Is it quantitative or qualitative?
3.3 What is the expertise required to use the tool?

Chapter 4: Sustainability coverage:

4.1 Which dimensions of sustainability are covered by the tool?
4.2 Does the tool use indicators? If yes, what indicators? And how are they measured and weighed?

Chapter 5: Operationalization:

5.1 What is the method or combination of methods used by the tool?
5.2 How does the tool function, from when it receives inputs to when provides outputs?
5.3 How is the method integrated in the company's processes? How are results used?

Chapter 6: Participants:

6.1 Who is using this tool? Is it used by employees or external experts? If employees, what departments are involved?
6.2 Are stakeholders outside the company involved, to share their interests or to provide additional knowledge?
6.3 Does the tool facilitate the information flow through different fields of knowledge?

The data is considered sufficient, incomplete or insufficient, when the source is able to answer all, any or none of the questions, respectively.

After conducting the source research, the final list of Eco-design tools can be selected. This selection aims at covering a wide variety of Eco-design tools, without compromising the feasibility of this research and thus a conservative number of tools needs to be selected. According to the time available to conduct this thesis, it is decided to compare the tools within three companies. It is believed that this sample of companies can provide enough insights to fulfil the purpose of this thesis.

In cases where the information gathered for a specific tool is not sufficient for more than half of the categories or it is discovered that the tool does not meet any of the requirements defined in the previous step, the tool is excluded for the comparison. In case of having selected tools that belong to more than three companies, some companies need to be excluded from the comparison or else the feasibility of the thesis can be compromised. This exclusion is based on the quality of information and the uniqueness of tools within the company. Tools that provide higher quality of information, and thus sources offer transparency on the six categories mentioned, are less likely to be excluded. Furthermore, tools with a distinctive feature that differs from the rest have lesser chances to be excluded. The reasons for every exclusion are transparently reported in the results section.

For the Eco-design tools selected, a thorough review of the sources is conducted and the information for each category is reported. The knowledge gained in this process is essential to have the right information to compare the Eco-design tools and to be able to extract fruitful insights from their application in the given companies. Furthermore, as it is addressed in the following step, understanding the tools serves as a basis to develop the screening method used to compare the tools.

2.3 Screening of the tools

After studying the tools, the screening method needs to be developed. The screening of tools has the objective to identify and describe the main characteristics of the tools, utilizing the knowledge gained from the previous phase 'understanding the tools'. This method builds a theoretical framework that serves to compare the functioning of the tools on the bases of a list of criteria. This screening results in a table that contains a qualitative description of the tools' mechanisms in relation to the set of criteria. The set of criteria is determined based on the goal and scope of this thesis. These criteria have to provide a fairly complete picture of how the tools function in the business context, but at the same time they need to be in accordance with the data collected in the previous phase. This is, the screening method should not demand deeper and further information about the tools, than what the 'understanding the tools' offers.

To develop this screening method, it is thus necessary to create the mentioned list of criteria, and to describe how they will be evaluated. For this purpose, three sources of data are used: (1) framework proposed by Broeren et. a. (2018), (2) knowledge acquired by 'Understanding the tools' and (3) studies that identified requirements Eco-design tools should meet. (1) The screening method shares the structure proposed Broeren et. a. (2018). This author's protocol serves as the foundation to create an adjusted screening method that meets the needs of this thesis. (2) As mentioned earlier, the knowledge gained from studying the tools serves to identify aspects shared by the tools and areas where they diverge, enabling their comparison and the identification of differences. (3) The third source of data helps to comprehend which tool's attributes are the most relevant to help companies integrate environmental considerations. The list of criteria has to enable the comparison of the attributes that, according to scientific literature, are considered important for the success of Eco-design strategies. The most relevant studies covering this topic were previously mentioned, Lofthouse (2006), Birch (2012) and Brundage (2018). For an automotive sector approach, Andriankaja et. al. (2015) and Singh et. al. (2020) can provide more case specific insights.

The mentioned data sources support the creation of a preliminary set of criteria. This list will be later compared to the evaluation criteria proposed by Broeren (2018). In case of discrepancies, criteria will be excluded or added to the evaluation method in order to adapt it to the research needs. The following are examples of criteria proposed by Broeren (2018) that can be directly applied for the evaluation of Eco-design tools: Transparency of indicators, consistency of system boundaries, reproducibility and required skills of the user. In this step a description of each evaluation criteria is given. This increases transparency and helps to minimise subjectivity and arbitrariness of the evaluation (van der Sluijs et al. 2005). The list of criteria is subject to changes along the thesis when new knowledge is gained, to iteratively improve the screening method.

2.4 Evolution of LCA within the automotive companies

The previous steps served to compare and comprehend how a sample of tools have been developed, adapted and operationalized in different automotive companies. Based on this gained knowledge, this next step is intended to deepen the understanding of the different LCA variants observed in the companies studied. This chapter aims at answering why companies developed or used the observed LCA methods. To do so it is decided to perform a historical contextualization of the content within the papers and publications issued by the automotive companies involved in this study. Historical contextualization is referred to the ability to situate phenomena in the context of time and long-term developments to give meaning to these phenomena (Van Boxtel & Van Drie, 2012).

The study presented by Guinee et al. (2011) 'Life cycle assessment: past, present, and future' lays down the framework for the historical contextualization. The author discussed the evolution of LCA from the conception and standardization of the method (1970-2000), to the so-called decade of elaboration (2000-2010). This analysis led to a forecast of where LCA was heading to, in the next decade (2010-2020). The study provides a suitable framework to argue the companies' LCA practices in time and to evaluate whether the companies were ahead or behind the last LCA developments.

2.5 Systematic model to drive Eco-design

The last step aims at defining the generic model that companies seem to follow when integrating Eco-design tools in their product development processes. This model has to describe companies' common strategy to drive Eco-design, through the utilization of a network of tools. With this definition, the previously gained knowledge on tools is used to converge into a final result. This final result formulates a sequence of processes, that assisted by tools, enables the systematic integration of Eco-design within companies.

The overarching goal of this step is the demonstration of the usefulness of the framework proposed in this thesis. How the analysis of a series of tools enable the practitioner to define a systematic approach to address Eco-design. A systematic approach that consists of a sequence of steps can be of the greatest value, as a guideline for companies that seek to start integrating Eco-design in their product development processes.

In order to define the sequence of steps, it is necessary to look at the goal of the tools, the questions they aim at answering. Those tools that have the same goal are considered exchangeable for one another, meaning that they belong to the same cluster. Whereas tools with different goals are considered complementary with each other. The different goals represent the different phases that conform the model, while processes derived from the complementary tools define the content within every phase. It has to be said that a single tool can have different goals.

This final result is supported by the knowledge gained through the screening (section 3.4) and the subsequent contextualization of the LCA variants (section 3.5). This screening enables us to explore and criticize aspects that are not accessible when treating the tools individually, and thus offers a new perspective from which to have a deeper understanding of the tool's properties and goals. Once the screening highlights the different life cycle approaches adopted by the studied companies, the contextualization of the LCA variants offers an explanatory framework that describes the roots of the diversity of approaches.

Chapter 3: Results

3.1 Pre-selection of Eco-design tools

In this section, a set of Eco-design methods is presented. These methods are considered to have the potential to provide new insights about the current Eco-design practices and future Eco-design trends in the automotive sector. For the selection of this preliminary list of methods, a thorough review is carried out of published scientific literature in this matter. This is combined with expert consultation to confirm the findings obtained from the literature review or to add new insights regarding current Eco-design practices in industry. To be selected in this stage, the method has to meet the requirement defined in section 2.1. The literature review leads to the identification of Eco-design tools within five car maker corporations.

BMW developed and integrated Life Cycle Sustainability Assessment (LCSA) for the design of components (Krinke et al., 2018). This method allows to balance economic, social and environmental interests, by using Life Cycle Costing (LCC), Social-LCA (S-LCA) and LCA, respectively (Tarne et al., 2017). This requires making trade-offs between economic growth, social cohesion and environmental protection. However, the goal of this method is to improve vehicle’s performance in all of the sustainability dimensions.

At Volkswagen Group, LCA is used to assess the environmental performance of different powertrains and fuels (Krinke et. al., 2018). This method is expected to play a key role to define future directions in line with the Group’s decarbonisation vision. Their findings showed that there is space for improvement in all powertrain systems. LCAs pointed out the importance of reducing environmental impacts related to lithium-ion battery production.

Groupe PSA has developed a method for integrating the environmental dimension into the innovation phase (Garcia et al., 2018). This method is focused on enhancing Group’s knowledge in the environmental field from a technical point of view, and ensures the integration of the environment in all organizational departments by providing users with the right tools and environmental recommendations. This method is characterized by its flexibility to be adapted when new lessons are learned and new knowledge is acquired.

Ford’s Product sustainability index is a management tool created to be used by vehicle development engineers and their management (Schmidt, 2016). According to Schmidt (2016) this approach enables the department of product development to assess the environmental contribution of their decisions, to set vehicle targets that lead to improvements in environmental performance and to visualize trade-offs between conflicting environmental measures, among others.

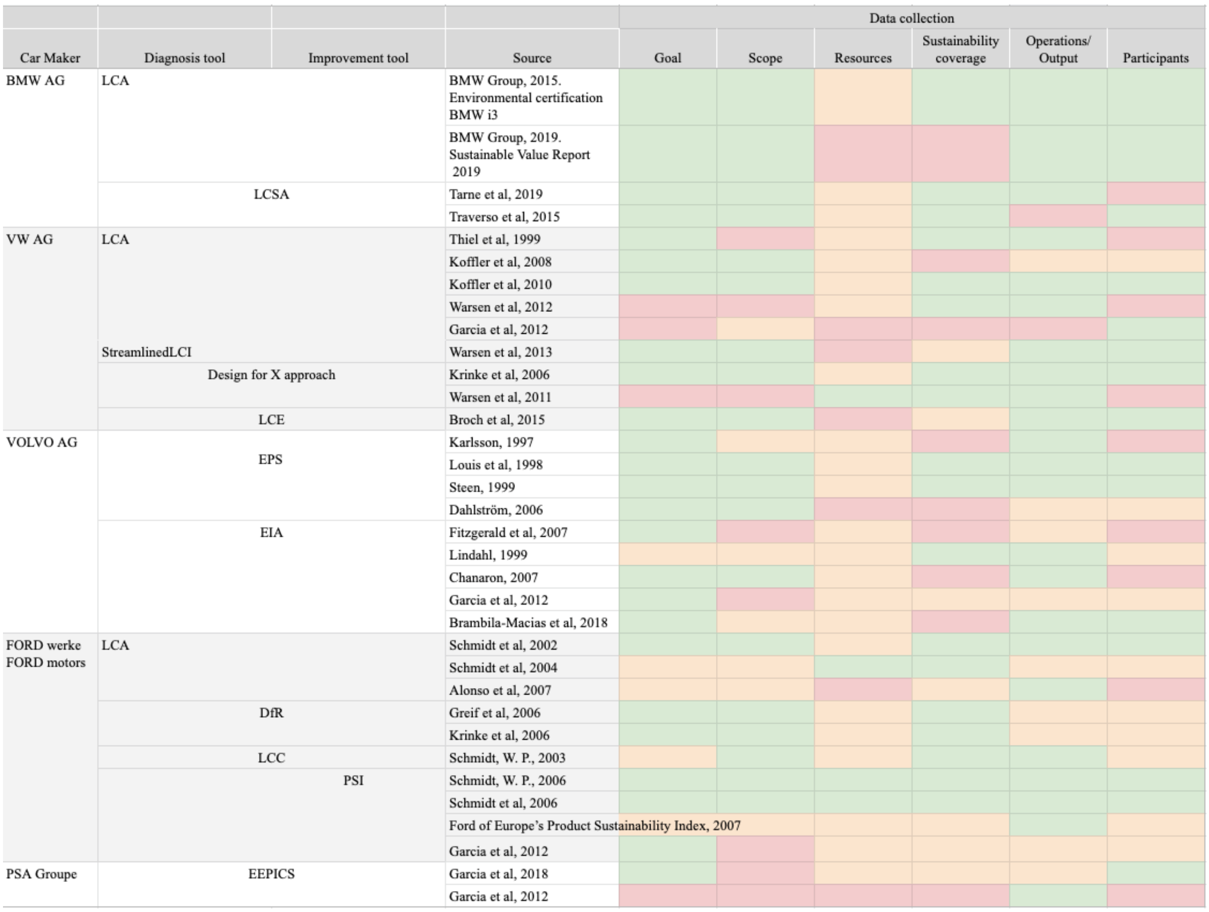
Volvo began doing research on LCA methods in the late eighties. Their coordination with other Swedish industries and research institutions lead to the development of Environmental

Priority Strategies (EPS), an LCA variant that was adopted by the company to improve the environmental performance of their vehicles (Louis et al., 1998). In combination with this quantitative impact assessment method the group also used a qualitative method known at the time as the Environmental Failure Mode and Effects Analysis (E-FMEA) (Chanaron et al., 2007). E-FMEA was a variant of the already existing FMEA method. Nowadays, E-FMEA is known as Environmental Impact Analysis (EIA).

After this literature review, the findings were shared with Peter Tarne, Specialist Product Sustainability at BMW Group and author of relevant scientific papers in the field, including the *“Review of Life Cycle Sustainability Assessment and Potential for Its Adoption at an Automotive Company”.* His feedback serves as a validation of the veracity and relevancy of the selected tools: “These constitute a good set of methods in order to compile a look at current ways of integrating sustainability in the automotive sector”. In the next chapter the quality of the available sources is evaluated in order to eventually select the definitive set of tools.

3.2 Understanding the tools

After selecting the preliminary list of tools, the available sources are evaluated to verify the availability of sufficient data. As explained in section 2.2, the publications are examined to determine whether they provide enough information about a set of categories, with the purpose of excluding the tools that do not meet the required standard. Table 1, shows the results of this assignment. The results showed that there is not sufficient data about the EEPICS developed by the PSA Groupe. In contrast the results showed that there is enough information about the rest of the methods that belong to four companies: BMW AG, VW AG, AB Volvo and Ford. As discussed in section 2.2, the analysis of four companies would compromise the quality of our study, and thus one of them has to be excluded from the study. Despite Ford representing an interesting subject of study, it is decided to select BMW AG, VW AG and AB Volvo for our study. This decision is taken because these three companies presented very unique and diverse pathways, and their tools are situated in very different periods of time. BMW AG can be characterized by their research in recent years on Life Cycle Sustainability Assessment, and their expressed concern to integrate sustainability considerations in their design process covering the three pillars society, economy and environment. Volkswagen on the other hand is characterized by its contribution to the elaboration of the LCA in the first decade of the 21st century, while Volvo already adopted an LCA approach, the Environmental Priority Strategies (EPS) during the nineties. In this context, the strategy of Ford is observed as a combination of these three, they also began doing research on sustainability indexes, contributed to the elaboration of LCA and the group acquired the knowledge of Volvo when Ford Motor Company bought Volvo Cars in 1999. For this reason, Ford was excluded from our study.



				Data collection					
Car Maker	Diagnosis tool	Improvement tool	Source	Goal	Scope	Resources	Sustainability coverage	Operations/ Output	Participants
BMW AG	LCA		BMW Group, 2015. Environmental certification BMW i3	🟩	🟩	🟧	🟩	🟩	🟩
			BMW Group, 2019. Sustainable Value Report 2019	🟩	🟩	🟥	🟥	🟩	🟩
	LCSA		Tarne et al, 2019	🟩	🟩	🟧	🟩	🟩	🟥
			Traverso et al, 2015	🟩	🟩	🟧	🟩	🟥	🟩
VW AG	LCA		Thiel et al, 1999	🟩	🟥	🟧	🟩	🟩	🟥
			Koffler et al, 2008	🟩	🟩	🟧	🟥	🟧	🟧
			Koffler et al, 2010	🟩	🟩	🟧	🟩	🟩	🟩
			Warsen et al, 2012	🟥	🟥	🟧	🟩	🟩	🟥
			Garcia et al, 2012	🟥	🟧	🟥	🟥	🟥	🟩
	StreamlinedLCI		Warsen et al, 2013	🟩	🟩	🟥	🟧	🟩	🟩
	Design for X approach		Krinke et al, 2006	🟩	🟩	🟧	🟩	🟩	🟩
			Warsen et al, 2011	🟥	🟥	🟩	🟩	🟩	🟥
	LCE		Broch et al, 2015	🟩	🟩	🟥	🟧	🟩	🟩
VOLVO AG	EPS		Karlsson, 1997	🟩	🟧	🟧	🟥	🟩	🟥
			Louis et al, 1998	🟩	🟩	🟧	🟩	🟩	🟩
			Steen, 1999	🟩	🟩	🟧	🟩	🟩	🟩
			Dahlström, 2006	🟩	🟩	🟥	🟥	🟧	🟧
	EIA		Fitzgerald et al, 2007	🟩	🟥	🟧	🟥	🟧	🟥
			Lindahl, 1999	🟧	🟧	🟧	🟩	🟩	🟧
			Chanaron, 2007	🟩	🟩	🟧	🟥	🟩	🟥
			Garcia et al, 2012	🟩	🟥	🟧	🟧	🟧	🟧
			Brambila-Macias et al, 2018	🟩	🟧	🟧	🟥	🟩	🟩
FORD werke FORD motors	LCA		Schmidt et al, 2002	🟩	🟩	🟧	🟩	🟩	🟩
			Schmidt et al, 2004	🟧	🟧	🟩	🟩	🟧	🟧
			Alonso et al, 2007	🟧	🟧	🟥	🟧	🟩	🟥
	DfR		Greif et al, 2006	🟩	🟩	🟧	🟩	🟧	🟧
			Krinke et al, 2006	🟩	🟩	🟧	🟩	🟧	🟧
	LCC		Schmidt, W. P., 2003	🟧	🟩	🟧	🟩	🟩	🟧
		PSI	Schmidt, W. P., 2006	🟩	🟩	🟩	🟩	🟩	🟩
			Schmidt et al, 2006	🟩	🟩	🟩	🟩	🟩	🟩
			Ford of Europe's Product Sustainability Index, 2007	🟧	🟧	🟧	🟧	🟩	🟧
			Garcia et al, 2012	🟩	🟥	🟧	🟧	🟧	🟧
PSA Groupe	EEPICS		Garcia et al, 2018	🟩	🟥	🟧	🟧	🟧	🟩
			Garcia et al, 2012	🟥	🟥	🟥	🟥	🟩	🟥

Table 1. Results from research of data sources. Green: sufficient. Orange: partially sufficient. Red: insufficient.

This chapter presents the results of the extensive literature review done on the selected Eco-design tools. The results are divided into three sections that correspond to the three companies involved in the study: BMW AG, VW AG and AB Volvo. Every of these sections contain the information gathered on the goal, scope, required resources, sustainability coverage, operationalization and participants of each of the tools adopted by the companies.

3.2.1 BMW AG

At BMW AG, LCA has been the main instrument to support Eco-design practices at the product level. The company published the results of the first certified LCA in 2013 (BMW Group, 2015), and since then several more LCAs have followed (BMW Group, 2018; BMW Group, 2019a; BMW Group, 2019b).

While LCAs have been integrated in the product development processes, researchers at BMW AG have been studying the possibility of integrating tools that include social impacts into the decision-making processes of vehicle design. Tarne et al. (2019) presents a framework to enhance the applicability of LCSA within the automotive industry. LCSA has the potential to guide designers in the implementation of measures to improve the sustainability performance of vehicles, by balancing impacts on all economic, social and environmental dimensions (Tarne et al, 2019).

The framework of Life Cycle Sustainability Assessment (LCSA) was developed by Walter Kloepffer and Matthias Finkbeiner (Klöpffer, 2003; Finkbeiner et al., 2008; Kloepffer, 2008; Finkbeiner et al., 2010). This framework suggests the combination of three life cycle analysis: Life Cycle Costing (LCC), Life Cycle Assessment (LCA) and Social Life Cycle Assessment (S-LCA). Each analysis addresses one sustainability dimension, respectively: economy, environment and society. As it is mentioned earlier in this thesis, LCA is a standardized method to assess the environmental impacts of products and services over their entire life cycle. In contrast with the LCA method, LCC and S-LCA are still not internationally standardized methods (Finkbeiner et al., 2010).

The following sections analyse the roles of LCA and LCSA to support Eco-design practices in product development processes at BMW AG.

3.2.1.1 Life Cycle Assessment (LCA)

i. Goal

The LCA has been used at BMW Group as a supporting decision-making tool in the development process of the car, to orient designers and engineers towards developing a car with a better environmental performance (Traverso et al, 2015). LCA is also used as an assessment method to compare different mobility concepts such as conventional and electro-mobility, public transportation and car sharing services (Traverso et al, 2015). LCA serves to understand and compare the potential environmental impact of developing these concepts (Traverso et al, 2015). Examples of decisions derived from the utilization of LCA: the increase in use of secondary aluminium and primary aluminium produced with renewable energy, the production of carbon fibre obtained with 100% hydropower in the BMW i3 (BMW Group, 2015), and improvement of recyclability of the car's components at the end of life (Traverso et al, 2015).

ii. Scope

This decision supporting tool addresses choices over the entire development process of cars, from product concept creation to the vehicle's start-of-production. Traverso et al (2015) claims that even though relevant improvements have been and are being achieved in the use phase, more needs to be done to reduce environmental impacts in the manufacturing phase.

Figure 2 is the simplified flowchart used in the LCA of the BMW i3 (BMW Group, 2015). The manufacturing phase involves the extraction of raw materials used in the components production, as well as the assembly and manufacture of the entire car. This flowchart shows the life cycles of the product, the components and some of economic and environmental flows considered in the assessment. Although not shown in this figure, apart from the recycling other EoL processes are included. In this LCA the reference flow is the BMW i3 BEV vehicle (model year 2014) with a use phase of 150.000 km, in line with the European driving cycle (BMW Group, 2015).

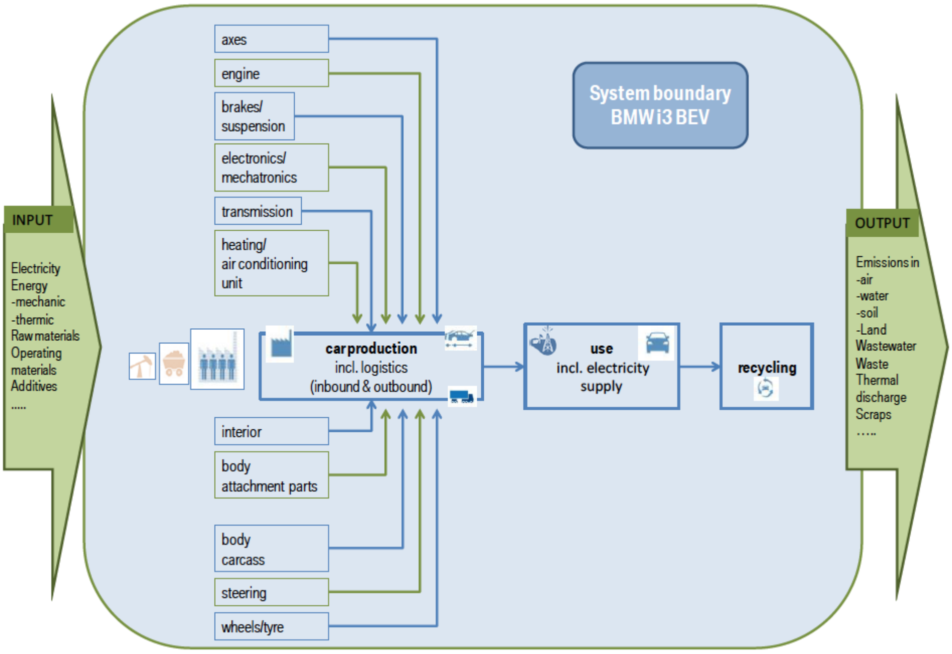


Figure 2. Flowchart input/ output data of the BMW i3 LCA. Retrieved from Environmental certification BMW i3 by BMW Group (2015).

iii. Required resources

The software and database used by BMW AG are Gabi and ProBas (GEMIS) (Traverso et al, 2015).

iv. Sustainability coverage

For years BMW AG has been focused on the environmental dimension of product sustainability. For that, special attention is given to Global Warming and the reduction of greenhouse gases emitted on the entire life cycle of cars. The rest of impact categories are also monitored, but with less impact in decision-making processes (Traverso et al, 2015). The impact assessment is based on the CML-method developed at Leiden University by Guinée and Lindeijer (2001).

Traverso et al. (2015) expressed the group's intention to integrate the economic and social dimensions, in addition to the environmental dimension covered by the current LCAs. The group recognizes that analysing only the environmental impacts of the car misses to address the economic and social impacts that must be considered to develop more sustainable cars. In response to this concern, in 2013 BMW Group was one of the founding members of the Roundtable of Product Social Metrics, among other companies like Philips or L'Oreal. This project resulted in the development of the *Handbook of Product Social Impact Assessment* (Goedkoop et al., 2018). This handbook aims at developing a common methodology to measure social impacts of products and services. In 2017, BMW Group presented the Life Cycle Sustainability Assessment LCSA method, with the intention of harmonizing all three dimensions to orient decisions towards development of sustainable cars (Tarne et al., 2019). This method is further analysed later in this thesis.

v. Operationalization

LCA is an internationally standardized method and its operational guide is presented by *the Handbook on life cycle assessment operational guide to the ISO standards* (Guinée et al., 2001). It consists of four phases: goal and scope definition, inventory analysis, impact assessment and interpretation.

In order to orient designers and engineers towards the development of environmentally friendlier cars, BMW AG sets measurable targets for the full life cycle of the given car in the earliest stage of the development process. Reduction targets can be established for each impact category by the company or derived from national environmental policies. In line with the targets established, a set of actions are undertaken over the whole value chain. The resulting global warming impact is monitored to ensure that the targets are met. When the concept of the car complies with the targets, the improvements of a car with respect to its previous model are assessed by conducting a final LCA. As requested by the ISO 14040 standard, the LCA process, data and results have to be validated by a third-party environmental verifier. Confidential knowledge gained from the LCA serves as a foundation for the development of new models. Additionally, reductions on global warming impacts are publicly shared in the Sustainability Value Reports (BMW group, 2019).

vi. Participants

LCAs are conducted internally by BMW AG. Traverso et al, 2015 says that the need to search for new potential improvements in the supply chain encourages the group to get closer to the suppliers and increases cooperation. This author addresses the difficulty of effective cooperation in a sector where the supply chain is particularly long and complex. A car consists of a great number of components, each produced by a large number of actors. To overcome this challenge, initiatives are carried out by stakeholders in sectors strongly related to the automotive sector. These initiatives aim at harmonizing methodologies, in order to promote the creation of a common language that facilitates communication of environmental issues within and among sectors. This is the example of the Aluminium Stewardship Initiative (ASI), where key players in the aluminium supply chain such as Rio Tinto and Novelis are involved, and where BMW AG showed its commitment together with other end-users such as Audi, Nestle or Nespresso (Traverso et al, 2015). Among a number of objectives, the ASI standard addresses the need for traceability of aluminium throughout the value chain, supporting the inventory data retrieval for a transparent LCA (Aluminium Stewardship Initiative, 2019).

Once LCAs are conducted at BMW AG, its results are used by the company to communicate the improvements on the environmental performance of their cars. However, these LCA studies are used to support internal decision-making processes and they contain confidential information that will not be shared with their competitors. In order to share their results and still protect confidential information that is key for the credibility of these studies, their validity is proofed by a third-party certification office, as requested by the ISO 14040 standard. This procedure is commonly used in the German automotive sector (Traverso et al, 2015).

3.2.1.2 Life Cycle Sustainability Assessment (LCSA)

i. Goal

Life Cycle Sustainability Assessment (LCSA) is a method that assesses the impact of a product over its entire life cycle on all three dimensions of sustainability. According to Tarne et al. (2019), this method has the potential to support engineers and designers in an automotive company to identify the components of the car with highest contribution to sustainability impacts and thus with the biggest improvement potential. The author's method also includes the Product Sustainability Budget (PSB), a method to identify the optimal set of improvements measures in the product development decision processes. However, LCSA appears to be of limited applicability, due to practical limitations such as the lack of data availability for social impacts, and (PSB) has still to prove its applicability in real-world applications (Tarne et al., 2019).

BMW AG supports the belief that to achieve sustainable development a correct assessment of products sustainability impacts must consider all three dimensions of sustainability. The study presented by Tarne et al. (2019) addresses the applicability of the LCSA framework in the automotive sector and brings BMW AG closer to the implementation of LCSA into product development processes. The implementation will serve to identify the components with the highest overall impact on sustainability, and to evaluate the best improvement measures at component or car level, derived from the overall LCSA impacts (Tarne et al., 2019).

ii. Scope

As proposed by Tarne et al. (2019), the LCSA is applied to the component level of a vehicle. Therefore, every component's impact is individually assessed to calculate the overall sustainability performance of a car as a whole.

LCSA's scope and system boundaries will be dependent on the ones utilized in the respective LCA, LCC and S-LCA. The scope of the LCAs currently conducted by BMW AG was discussed in the previous section. For LCC and S-LCA, Traverso et al. (2015) and Tarne et al. (2019) do not present clear guidelines on this regard, but they identify a number of methodological choices that have to be faced when defining the scope of each of these methods.

As mentioned before, LCC compiles and assesses costs associated with the life cycle of a product for a specific set of stakeholders in its life cycle (Hunkeler et al., 2008). As stated by Traverso et al. (2015), LCC results are strongly influenced by the chosen stakeholders. This happens because some costs are borne by different actors with very different perspectives of the costs and potentially conflicting goals (Swarr et al., 2011). For instance, considering the costs and revenues related to a manufacturing company or focusing more on the costs related to the consumer can lead to very different conclusions (Traverso et al., 2015). This observation highlights the importance of defining a scope that matches with the question that the LCC aims to answer, and thus the perspective from where the problem is addressed is key. For instance, Tarne et al. (2019) suggests that for the assessment of a component's economic impact in the use phase, its frequency of replacement and its warranty conditions need to be addressed, to determine who bears the costs of the replacement (manufacturer or customer). This can be observed in one of the LCC analyses published by a doctoral researcher at BMW AG. Diaz et al. (2011) performed an LCC analysis comparing the costs of different electric powertrains ranging from mild hybrids to a BEV. The author's LCC model aimed at calculating both costs to the manufacturer and costs to the consumer.

S-LCA assesses social performance of a product over its life cycle and for that it considers at least five main stakeholder groups: workers, customers, local communities, society and the rest of value chain actors (Andrews et al., 2009). However, in practice the social impacts are usually considered only at corporate level and the assessment rarely goes beyond the first line of suppliers (Traverso et al., 2015). This conflicts with BMW AG's vision to integrate results of corporate social performance in the development of more sustainable cars. Tarne et al. (2019) addressed this issue by presenting a framework that facilitates the definition of a scope and selection of social indicators, and proposed a method for social hotspot assessment in the supply chain of components.

iii. Required resources

At BMW AG, the environmental and economic dimensions are already implemented (Tarne et al., 2017). The data used in the LCAs is mainly supplied by the Gabi and ProBas (GEMIS) software (Traverso et al, 2015). In contrast with LCA, LCC requires data from a wider range of sources. As an example, the following are some of the data sources that were required in the LCC analysis by Diaz et al. (2011): cost of electricity and fuel was taken from 2009 forecasts from the Energy Information Agency; values for fuel and electric consumption were estimated using PSAT, a powertrain simulation tool; the costs of repairs and maintenance were estimated using data taken from EDMUNDS.COM 2009.

On the other hand, at BMW AG the integration of S-LCA methods in the product development processes is still limited. This is in part due to a lack of a broadly consensual handbook that guides primary data collection in S-LCA (Tarne et al., 2019). According to Tarne et al. (2018a), Multi-Regional Input-Output databases such as Eora, EXIOBASE, GTAP and WIOD, do not offer robust results, as their results vary significantly between each other and also the real-world supply chain that they are supposed to model. In order to fill this gap, Tarne et al. (2019) presents an alternative approach that facilitates a streamline primary data collection for social hotspot assessment.

This new approach uses the Social Hotspot Database (SHDB) as the main source of data on social risks (Tarne et al., 2019). SHDB collects international data on social topics like child labour, forced labour or labour rights (SHDB, n.d.). The first step consists in identifying the social risks associated with all relevant materials used in the life cycle of vehicle components (e.g. steel, aluminium, lithium, copper, plastics). Secondly, to assess the risks associated with buying those materials from the worldwide market, the risk data from SHDB is combined with data about the materials consumed by the company, regarding material volume and origin.

iv. Sustainability coverage

LCSA is a method that covers the three dimensions of sustainability, in order to support decisions for measures that aim at improving the overall sustainability performance of products. According to Tarne et al. (2017) this LCSA framework has not been fully adopted at an automotive company level for the mentioned purpose. In the following section, we discuss the indicators that are used per dimension and the method proposed to combine them.

As mentioned earlier, the indicators used in the LCAs are based on the environmental impacts suggested by the CML-method. So far, the LCAs published by BMW AG focus mainly on the reduction of Global Warming impacts (LCA reports sources). However, the LCSA method proposed by Tarne et al. (2019) allows the combination of different environmental impacts (i.e. effects on the depletion of fossil fuel and raw materials, global warming, eutrophication and marine and terrestrial ecosystems) to calculate an overall environmental performance. To do so, once the LCA calculates the environmental impacts of the vehicle components, the VIKOR method is applied (Opricovic & Tzeng, 2004, 2007). This method serves to combine the results of different impact categories to create a single LCA criticality indicator per vehicle component. Although, firstly the practitioner has to weigh the different impact categories, according to the priority that is given to each of the impacts. Due to this weighting, impact categories have more or less influence in the overall environmental indicator. A final step awards with 100 LCA criticality points to the component with the highest overall impacts, and with 0 to the component with the lowest overall impact.

Similarly, to LCA results, the costs resulting from the LCC analysis are also transformed into LCC criticality points, by applying the VIKOR method. LCC can be used to assess both economic and environmental performance of a product (Traverso et al., 2015). The assessment of environmental performance is achieved by internalizing the costs of the environmental impacts, by applying the polluter pays principle, or by using information to make the impacts explicit at the time of the decision (Swarr et al., 2011). As LCC is also a tool to measure environmental impacts, attention needs to be paid to avoid double counting the same impacts in both LCA and LCC.

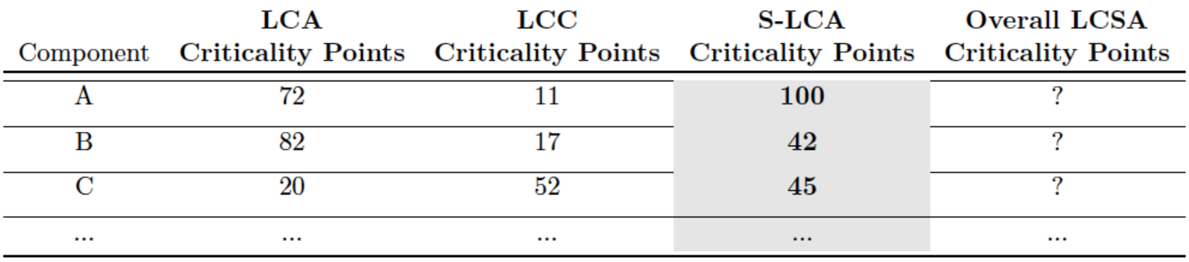
Regarding S-LCA, researchers claim a lack of consensus on the most relevant impact categories and indicators to consider (Kühnen & Hahn, 2017). Tarne et al (2019) presented a mechanism to select social topics relevant to the company and to deduct their corresponding indicators. In the first step a materiality matrix is used to classify social topics regarding their level of priority for the BMW AG and stakeholders. To gather stakeholders' expectations telephone interviews and surveys conducted to representative stakeholders, including customers, suppliers, investors, authorities, NGOs and scientists. Meanwhile, knowing the internal perspective involved carrying out workshops with representatives from the relevant company departments. At BMW AG, this process led to the identification of the following top priority social topics: human rights, social standards in the supply chain, occupational health and safety, and corruption. After selecting social topics, the corresponding indicators are defined. For that the list of indicators of the SHDB is reviewed to select the ones that match with the social topics identified. The following are the indicators selected in the case of BMW AG to cover the four social topics:

- Human rights
    - Risk of child labour
    - Risk of forced labor
    - Risk of violation of right to collective bargaining
    - Risk of violation of right of freedom of association
- Social standards in the supply chain
    - Potential of Average wage being < Minimum Wage
    - Risk of excessive working time
- Occupational Health and Safety
    - Risk of non-fatal injuries
    - Risk of fatal injuries
- Anti-Corruption / Compliance
    - Overall Risk for Corruption

Once the indicators are selected, Tarne et al (2019) proposes a criterion to quantify these indicators, by presenting formulas that calculate a risk score related to every material within a given component. The input data for these formulas is retrieved from the SHDB. These are the steps involved to calculate the overall social risk score of a single component : (1) Identification of all relevant materials needed and their required mass per component (2) Identify the processes required to generate these materials, and the volume of material these processes produce per countries, from a material-based assessment (3) Using SHDB find the risk scores (i.e. child labor, forced labor, violation of rights) related to every process per country (4) include this data in the formulas and calculate a single social risk score related to a kilogram of every material (5) knowing the risk related to every material unit and the material needed every component, it is possible to calculate the overall risk score of each component of the vehicle. One of the particularities of the method proposed by Tarne et al. (2019), is that some indicators such as the risk of child or forced labor are considered as a knockout criterion. This means that if one of these represents a very high risk, the risk score of the entire social topic would also be considered as very high risk. In this way, the method allows to consider some social risks as unacceptable and the scores shifts to the highest risk without considering the rest of social indicators.

v. Operationalization

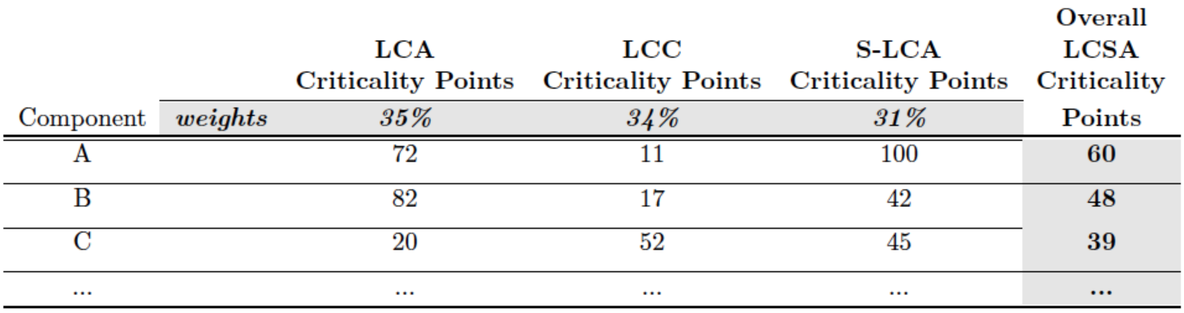
After LCA, LCC and S-LCA are applied to the component level of the vehicle, the results are unified by transforming them into criticality points, using the VIKOR method as explained above. This leads to the unification of the impacts over the three dimensions of sustainability, as shown in figure 3.



Component	LCA Criticality Points	LCC Criticality Points	S-LCA Criticality Points	Overall LCSA Criticality Points
A	72	11	**100**	?
B	82	17	**42**	?
C	20	52	**45**	?
...	...	...	...	...

Figure 3. Criticality points per component retrieved from the results of LCA, LCC and S-LCA. Retrieved from Tarne et al. (2019).

Once the criticality points per dimension are obtained, Tarne et al. (2018b) proposes a method for decision makers to interpret LCSA results. This method requires a Limit Conjoint Analysis aimed at weighing the priority of sustainability dimensions. In this process, decision makers are asked to rank different alternatives of a vehicle component with different impacts on the three sustainability dimensions according to their preference of use within the vehicle. This ranking serves to weight the priority of the dimensions. In the case of Tarne et al. (2018b), the 3 dimensions were weighted almost equally. This weighting results in the overall LCSA criticality points per component, as shown in figure 4.



		LCA Criticality Points	LCC Criticality Points	S-LCA Criticality Points	Overall LCSA Criticality
Component	***weights***	***35%***	***34%***	***31%***	Points
A		72	11	100	**60**
B		82	17	42	**48**
C		20	52	45	**39**
...		...	...	...	**...**

Figure 4. Weighting of the criticality points and calculation of the overall criticality points. Retrieved from Tarne et al. (2019).

In theory, this LCSA framework works to identify which components cause the highest impacts in terms of product sustainability, and serves to evaluate and identify new improvement measures to reduce them. However, at a company level these measures may not be implemented in cases where benefits on the social or environmental dimensions deteriorate the economic one. This happens because on the existing decision processes the economic dimension is treated with higher priority (Tarne et al., 2019). This makes it highly unlikely to implement improvement measures that cause an increase in costs.

To address this problem Tarne et al. (2018c) introduced the Product Sustainability Budget (PSB). The PSB allows practitioners to evaluate the economic benefits that the sustainability improvements bring. In this way, compensating the additional costs these measures carry. In order to calculate the PSB, Tarne et al. (2018c) proposes a study of the Willingness to Pay (WTP) of customers for customer relevant sustainability features.

This LCSA framework has demonstrated potential for identifying sustainability hotspots of a vehicle, and for supporting the implementation of sustainability improvement methods in decision making processes. However, its applicability has still to be proven at the company level.

vi. Participants

As the LCSA is still not fully integrated at BMW AG, it is challenging to identify all the actors involved. Although, the previous sections have shown that LCSA requires the participation of several players external to the firm. For instance, the identification of the relevant social topics involves both external and internal actors, such as customers, suppliers, investors, authorities, NGOs and scientists. This allows BMW AG to address the social issues that are important not only for the company, but for a wide range of societal groups too. Another example is the PSB which requires consulting customers, in order to measure their WtP for sustainability features. In this manner, customer preference plays an important role shaping vehicles sustainability improvement measures.

3.2.2 VW AG

VW AG began research on LCA in the early 1990s. In 1996, the company became the first car maker in preparing and publishing a LCI for the Golf III, and in the following years LCIs were published for various other vehicles. Years later, LCAs have become an integral part of the companies' product development processes (Warsen et al., 2012). Apart from using it the group has also contributed to the improvement of LCA methodology, focused largely on its applicability within the automotive sector. This required the collaboration of research institutions. A first example of this can be seen in Thiel et al. (1999), presenting an integrated approach for assessing local and regional impacts within LCA. Years later, Volkswagen created the slimLCI, a procedure to streamline inventory modelling within LCA of vehicles (Koffler et al., 2008). In 2010, the group also contributed to the improvement of the use phase modelling by introducing the so-called Fuel Reduction Value parameter (Koffler et al., 2010).

Since 2007, the Volkswagen brand has published Environmental Commendations (EC) which inform customers and the general public about the environmental performance of new models in comparison to their predecessors (Volkswagen AG, 2010a; Volkswagen AG, 2010b; Volkswagen AG, 2013). These ECs are based on detailed LCA studies performed by the company. By the end of 2013, VW Passenger Cars and Volkswagen Commercial Vehicles had published 18 Environmental Commendations (Broch et al., 2015).

The LCAs result in the identification of environmental hotspots. These findings serve VW AG to define which parts of the vehicle's supply chain deserve more attention, and thus concentrate their efforts on the development of specific improvement measures. This leads to new LCAs aimed at evaluating the measures with potential to address the identified hotspots, and assessing the possible burden shifting from one life cycle stage to another. The company mainly focused on reducing the environmental impacts caused by the vehicle's EoL. Garcia et al. 2012 defined VW's strategy as Design for Remanufacturing and Design for Recycling. This thesis addresses both as a single method named Design for X approach (DfX), as both tools serve to evaluate the entire life cycle environmental performance of measures within a specific life stage. Even though DfX within VW AG can be considered as a type of LCA, its unique features deserve to be treated as a different tool.

In 2015, VW AG presented Life Cycle Engineering (LCE), a management tool to derive measurable technical targets from LCA results (Broch et al., 2015). This method shows how to interpret LCA results and create specific targets that employees, without LCA expertise, are familiar with. These targets are adapted to the function and expertise of the engineers that need to pursue them. For instance, in case the LCA shows that the EoL stage can be improved by increasing the recyclability of a component, a suitable target would be the percentage of recyclable material that a component needs to contain to fulfil the envisioned environmental targets.

In the field of Eco-design, the overarching goal of the company is to develop each model in such a way that, over its entire life-cycle, it presents a better environmental performance than its predecessor (Warsen et al., 2013). The next sections will explain the main features of the most relevant Eco-design tools utilized to pursue that goal: LCA, DfX and LCE.

3.2.2.1 <u>Life Cycle Assessment (LCA)</u>

i. Goal

At VW AG, the purpose of LCA studies is to evaluate the environmental performance of vehicles over their entire life cycle. The results serve to identify which processes cause the highest environmental impacts, and thus the ones that deserve more attention. The results of these LCA studies behave as the knowledge foundation required to develop technical targets and measures for the improvement of a vehicle's environmental performance (Broch et al., 2015).

Since 2007, LCA has been also used as a communication tool (Warsen et al., 2011b). When the environmental measures are applied and the vehicle design is completed, LCA confirms that the vehicle has met its targets. This LCA leads to the so-called Environmental Commendations (EC), where VW AG documents the ecological progress in a vehicle compared to its predecessor (Warsen et al., 2011b). ECs provide customers, shareholders and stakeholders inside and outside the company with information about the achievements regarding vehicles' environmental improvements. To ensure the reliability of these documents, the LCA results are reviewed, verified and certified by independent experts, in line with the requirement of ISO 14040 (Warsen et al., 2012).

ii. Scope

ECs offer a good overview on the scope of this LCA study. To analyse this scope, the following text analyzes the Volkswagen's Environmental Commendation for the e-up! (Volkswagen AG, 2013).

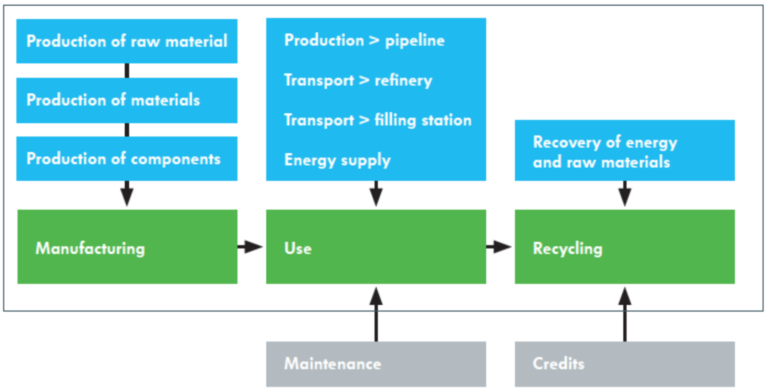


Figure 5. Schematic diagram representing the scope and system boundary in the LCA of the VW e-up! Reprinted from The e-up! Environmental Commendation – Background Report (2013).

Figure 5 illustrates the scope of the VW e-up! LCA. At VW AG, the scope of LCAs is defined to account for all relevant processes and substances related to the main stages of the vehicle's life cycle, covering from the production of raw materials to the EoL vehicle treatments (Volkswagen AG, 2013). The vehicle manufacturing phase includes all manufacturing and processing stages for all vehicle components. The use phase covers the fuel supply process, including shipment from the oilfield to the refinery, the refining process and transportation to the filling station. The electric power supply includes power generation, network losses and provision at the charging point. Vehicle maintenance is not included in the LCA, because according to a previous research maintenance has a negligible environmental impact (Volkswagen AG, 2013). The recycling phase is modelled in accordance with the Volkswagen SiCon process. Using this process, an average of 95% of the weight of an EoL vehicle is recycled and used as a substitute for primary raw materials. Regarding the lithium-ion, the dismantling of the components is considered but its recycling is left out of the scope. Additionally, the secondary raw materials obtained from the recycling phase leave the system boundary, and thus the potential positive environmental impact due to a reduction in primary raw materials is not considered. The functional unit used is the "Transport of passengers over a total distance of 150,000 kilometres in the New European Driving Cycle (NEDC), with comparable utilisation characteristics (e.g. performance)" (Volkswagen AG, 2013).

iii. Required resources

VW AG paid special attention to the collection of data required and manpower involved in the LCA studies. Koffler et al. (2008) identified an issue concerning Life Cycle Inventory (LCI) modelling. LCAs conducted by the company involved a good share of expert knowledge and an excessive amount of manpower. This and the limited time frame of the studies affected the quality of LCA results. In order to address this issue, Koffler et al. (2008) presented Volkswagen slimLCI, an automatize procedure for streamlined inventory modelling within LCA of vehicles. The maximum period of time required for an LCI was around seven months and this is reduced to six weeks when using VW slimLCI (Koffler et al., 2008). The author also argued numerous advantages concerning LCA quality. For instance, the procedure provides practitioners with reliable assumptions in case that no specific information is found about manufacturing processes.

The EC of the VW e-up! shows the sources of the data required for the LCA study (Volkswagen AG, 2013). As defined in the document, data can be divided into three categories. The first category includes the information on parts, quantities, weights and materials. This information is developed following the VW's slim LCI methodology. The second includes the information on fuel consumption and emissions during use phase. For this, representative data for upstream fuel supply chains are retrieved from the Gabi database. Finally, the information on recycling volumes and processes is modelled on the basis of data from the Volkswagen SiCon process and it is combined with representative data from the GaBi database.

The software required to conduct the LCA study is the GaBi 6. Additionally, GaBi DfX and slimLCI interfaces are used as support tools (Volkswagen AG, 2013).

iv. Sustainability coverage

The environmental impacts assessed by the LCA are included in the CML methodology developed by Guinée and Lindeijer (2001). The impact categories chosen by VW AG are the following: eutrophication, ozone depletion, photochemical ozone creation, global warming and acidification potential (Volkswagen AG, 2013). The choice is based on the priorities of the Sixth Environmental Action Programme of the European Community. These categories are also considered particularly important for the automotive sector as VW AG states in all their EC commendations.

v. Operationalization

At VW AG, the operationalization of LCA follows the guidelines presented by *the Handbook on life cycle assessment operational guide to the ISO standards* (Guinée et al., 2001). It consists of four phases: goal and scope definition, inventory analysis, impact assessment and interpretation. LCA is performed continuously in parallel to the product development processes, spanning phases such as research, advance engineering, definition of vehicle targets, characteristics catalogue and performance specifications (Warsen et al., 2012). In the final stage, when the vehicle design is completed the final LCA results are reported and verified by independent experts, leading to the development of the EC.

vi. Participants

All LCA studies mentioned were conducted by the Environmental Affairs Product Department at VW Group Research in Wolfsburg. In order to ensure the protection of confidential information and in accordance with ISO 14040/44 standards, the LCA process, data and results are eventually validated by a third-party environmental verifier, e.g. by TUV NORD (Volkswagen AG, 2013).

3.2.2.2 Design for X approach (DfX)

i. Goal

At VW AG, Design for X approach (DfX) studies serve to evaluate the benefits of environmental measures in the vehicles supply chain, by comparing their environmental impacts to the ones of traditional practices. These measures seek to reduce the impacts of a specific component or process in the vehicles' life cycle. In addition to that, these studies need to ensure that the environmental impact of the measures has an overall positive impact over the vehicles entire supply chain, and thus preventing the burden shifting between life cycle stages or processes. For that a life cycle approach is essential and that is why the company uses LCA to support the DfX studies. Krinke et al. (2006) and Warsen et al. (2011a) are the best examples of the implementation of DfX at VW AG.

Krinke et al. (2006) explores the improvement of vehicles' environmental performance from a Design for Recycling approach. The author assessed the environmental impacts of the Volkswagen-SiCon process, an innovative treatment of end-of-life vehicles aimed at bringing both economic and ecological advantages. In this LCA study, the environmental performance of the VW-SiCon process was compared with a dismantling scenario based on mechanical recycling. The results showed that the innovative treatment had a better environmental performance in terms of Global Warming, Acidification, Summer Smog and Eutrophication. The study served to confirm the benefits of this new EoL treatment and help to boost the construction of VW-SiCon treatment plants (Krinke et al., 2006).

On the other hand, Warsen et al. (2011a) looks at potential environmental improvements from a Design for Remanufacture approach. In this LCA study, the environmental performance of a remanufactured component is compared to its newly manufactured unit. The results showed the environmental benefits of the remanufactured alternative. In this case study the emissions caused by the transportation of used transmissions highly compensate the emissions of the avoided consumption of energy and materials related to newly manufactured components. The results highlighted the importance of designing components in a way that facilitates their remanufacture.

ii. Scope

At VW AG, the scope of DfX studies differ considerably from those of the complete LCAs, mentioned in section 3.2.2.1. In contrast with complete LCAs, DfX focuses on a specific system within the vehicle's life cycle. This allows practitioners to zoom in the processes that are causing the biggest environmental damage, by breaking processes into more elementary subprocesses. In this way it is possible to have a deeper understanding of what causes the environmental impacts, and thus it becomes easier to find solutions to minimize them.

Krinke et al. (2006) focused on the vehicle's EoL phase. The functional unit chosen is a reference EoL vehicle for recycling/recovery. This reference EoL vehicle is defined in accordance with a representative EoL vehicle mix in 2015, which included various equipment packages and derivatives of two of the best-selling vehicles in Europe. Figure 6 shows a simplified diagram of the processes included in the study. The model includes all processes for the treatment of EoL vehicles from draining and dismantling of mandatory components to the final disposal of unrecovered materials. The VW-SiCon model includes an additional treatment of shredder residues, where the PVC fraction and the smallest metals are recovered for recycling.

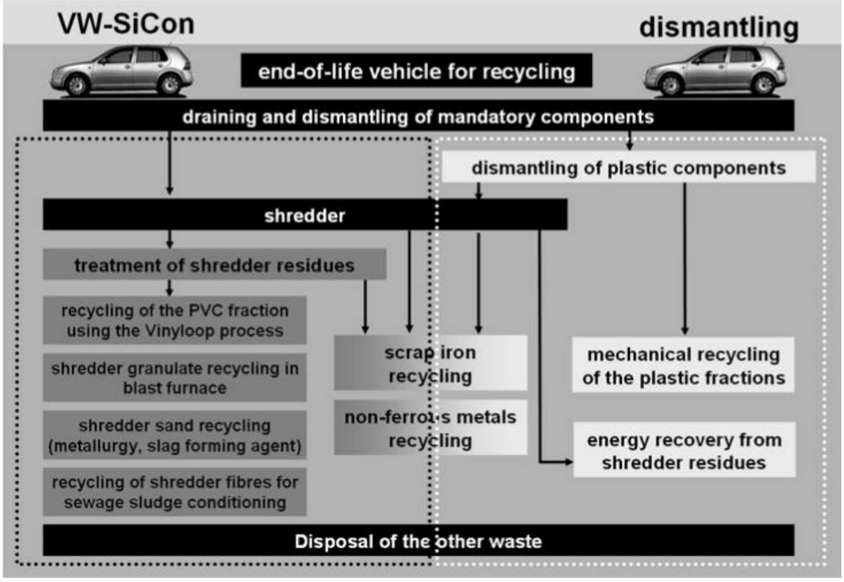


Figure 6. Scope of the comparative life cycle assessment. Retrieved from Krinke et al. (2006).

Warsen et al. (2011a) focused on the manufacturing and remanufacturing phases of a transmission component. The functional unit was defined as the manufacture of a manual 5-speed MQ 250 transmission, Volkswagen’s highest-volume transmission at the time. Figure 7 shows a simplified diagram of the processes modelled. The model includes all steps from extraction of raw materials and the manufacture of semi-finished products to their assembly. The remanufacturing phase covers the transport of the old transmission to the plant, the dismantling, cleaning and testing of the old transmission, the production of replacement parts and the reassembly of the transmission. The use phase of both alternatives is considered identical as remanufactured transmissions meet the same technical requirements as newly manufactured units. Thus, the use phase is left outside the scope of the assessment. Same happens to the recycling phases as they are also assumed to be identical for both alternatives.

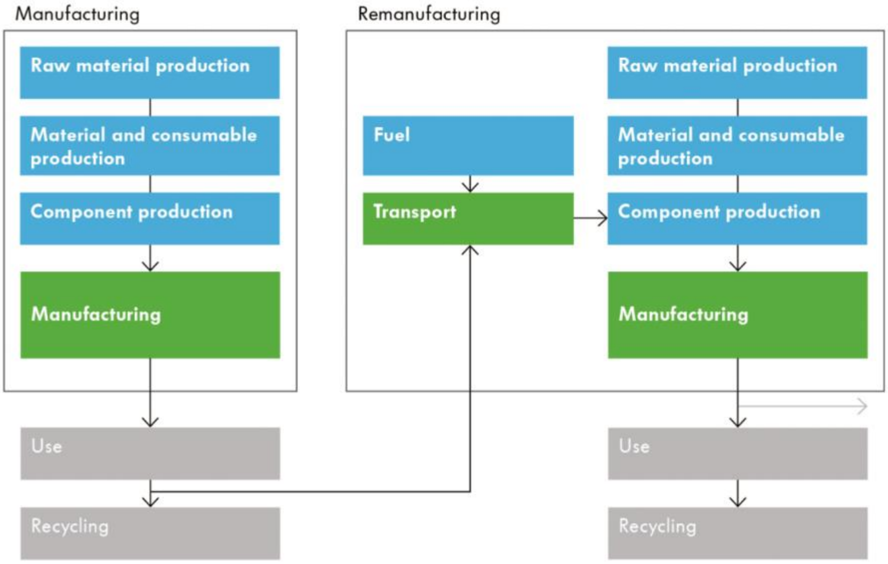


Figure 7. Scope of the comparative life cycle assessment. Retrieved from Warsen et al. (2011a).

DfX studies highlight the importance of choosing the right scope to evaluate the environmental performance of environmental measures. Both studies presented arguments to support their decisions in terms of scope and functional unit definition. Transparency in this regard is crucial to interpret the results in accordance to the assumptions made by the LCA practitioners. In these studies, a big part of the vehicles supply chain was left outside the system boundary. It was assumed that the technologies compared have identical environmental impacts outside the assessed life cycle phase, but this is not always true. As happens in Warsen et al. (2011a) and Krinke et al. (2006), this assumption is more likely to be suitable because the EoL of a product is considered as the final stage of its life cycle and it less likely that influences other life cycle's environmental impacts. For instance, this is different when assessing the environmental profile of a component's alternative material, which will undoubtedly influence processes over the vehicle's entire life cycle.

iii. Required resources

In terms of data collection DfX studies are in principle similar to the complete LCAs analysed in section 3.2.2.1. The systems are modelled using the same VW slimLCI methodology and the models are later linked to the corresponding process data in the LCA software GaBi (Warsen et al., 2011a). However, the collection of data can raise in complexity when trying to model innovative processes. This is often the case of DfX studies where practitioners aim at evaluating the effects of innovative components, materials or technologies, whose properties are still not covered by databases.

In particular, the development of the VW SiCon process required the expertise of different technology partners along the added-value chain. This included the collaboration of potential plant operators and customers for produced material fractions (Krinke et al., 2006). The study also required specific data of an innovative process that was not covered by conventional databases. For this reason, the authors had to retrieve empirical data from some of the several large-scale tests of the VW SiCon process, conducted by researchers at VW AG (Krinke et al., 2006). For the second study, knowledge from internal experts of powertrain remanufacturing was required (Warsen et al., 2011a).

iv. Sustainability coverage

In terms of sustainability coverage, DfX studies are identical to the LCAs analysed in section 3.2.2.1. Krinke et al. (2006) and Warsen et al. (2011a) both considered the following category impacts: Global Warming, Acidification, Photochemical Ozone Creation, Ozone Depletion and Eutrophication.

v. Operationalization

To a large extent the operationalization of DfX is identical to the LCAs of section 3.2.2.1. One of the main differences is that these studies do not lead to the development of EC documents. The results of these studies are utilized internally, for example integrating their findings into future LCAs. Apart from that, DfX studies are characterized by a more thorough sensitivity analysis. As mentioned before (‘required resources’ section), DfX is based on data that is complex and subject to uncertainties. The sensitivity analysis aims at analysing the effects of data fluctuation, and thus serves to analyse the robustness of the obtained results. For instance, Krinke et al. (2006) studied the influence of variables in the environmental results, such as the amount of plastics separated into single type materials or the composition of EoL vehicles.

vi. Participants

DfX studies are conducted by the research group of the Environmental Affairs Product department (Warsen et al., 2011a), and the Recycling and LCA department (Krinke et al., 2006). In the case of Warsen et al. (2011a) a collaboration within the company was required between the LCA practitioners and experts from the department of powertrain remanufacturing. On the other hand, for the development of the VW SiCon process external experts on vehicle’s EoL treatment were consulted.

These examples highlight the importance of collaboration when it comes to evaluating ecological measures aimed at improving vehicles’ environmental performance. Collaboration serves to share expertise within different knowledge fields. In both studies analysed, this interdisciplinary knowledge was proved essential in the development of realistic models that simulate the effect of ecological measures. Collaboration also provided information about the interests and limitations of supply chain actors who play a key role in the implementation of the studied ecological measures. This was the case of the VW SiCon project, where potential plant operators and customers of the products produced by the VW SiCon process shaped the development of the process at an early stage (Krinke et al., 2006).

3.2.2.3 Life Cycle Engineering (LCE)

i. Goal

As explained in the previous sections, VW uses the LCA methodology to analyse the environmental performance of vehicles and to identify ecological hotspots therein. These findings serve to determine which improvements will have the greatest environmental effect. According to Broch et al. (2015), the fundamental aim of LCE is the management and controlling of measures for the improvement of the environmental profile of products. For that, it is necessary to transfer the knowledge acquired from LCA into realistic and convertible improvements. In other words, LCA results have to be translated into technical goals, which are expressed in a context that is sufficiently specific to allow decisions and measures from an engineering point of view (Broch et al., 2015).

The LCE approach utilized at VW AG was illustrated in a case study performed by Broch et al. (2015). With the example of lightweight design, the study shows the implementation and application of LCA derived technical targets. Lightweight design is a measure aimed at lowering the car's fuel consumption and driving emissions (Broch et al., 2015).

ii. Scope

The LCE approach focuses on measures that improve the environmental profile of the vehicle over its entire life cycle. These measures include decisions regarding the selection of components' material, geometry and feature, and the processes involved in the components' life cycle. Examples of improvement measures are components' weight reduction, fuel reduction technologies or the increase of secondary material.

Broch et al. (2015) shows the application of the LCE approach for a component's lightweight design. In lightweight design it is crucial to understand the potential of secondary weight effects and to choose the right materials to avoid shifts of environmental burdens (Warsen et al., 2012; Broch et al., 2015). Secondary weight effects refer to the possible improvement measures that flourish from vehicles' mass reduction. According to the group, the reduction in vehicle weight should lead to an adaptation of powertrain size. Studies support that an adapted powertrain significantly improves the environmental benefits of lightweight design, more than doubling the reduction of tailpipe-emissions from 3.6 to 8.2 g CO2/km (Rohde-Brandenburger, 2014; Broch et al., 2015).

In the case study, Broch et al. (2015) divides the environmental emissions into the following three life cycle phases: production phase, use phase and EoL phase. The production phase covers the raw material extraction, semi-finished products or components production and finally the vehicle's assembly. The use phase covers the tailpipe emissions and the emissions related to the fuel extraction and production. At the EoL the vehicle is assumed to follow the SiCon process, where it is partly dismantled and shredded for the recycling of the materials. In the evaluation of improvement measures and derivation of measurable targets, the system analysed is delimited by the processes affected by the studied measures. For instance, the comparative LCA between conventional cold stamped steel and hot stamped steel only covers processes related to the production, use phase and EoL of this material. The rest of the process not covered by the LCA are considered identical for both material options.

iii. Required resources

LCE requires a comparative LCA of the vehicle's design alternatives. LCA results serve as the knowledge foundation to support improvement measures.

iv. Sustainability coverage

At Volkswagen the LCE approach is based on LCA results, and thus the proposed measures only address the environmental dimension of sustainability. The group believes in the importance of deriving measurable technical targets and indicators, to influence developments in Eco-design at vehicle level. According to Broch et al. (2015), these technical targets must fulfil the following requirements:

- Address factors that have a considerable influence in a vehicle's environmental impact.
- Be suitable on a universal scale and not bound to specific assumptions.
- Use a language that is familiar to the recipient, such as the decision makers, engineers or designers in charge.

Broch et al. (2015) shows an example of a suitable technical target and shows how it is calculated using the environmental impacts resulting from an LCA study. In lightweight design the decisive factor to assess a design is the weight reduction in comparison to a reference. A weight reduction target value expresses the necessary weight reduction that is required to obtain a significant improvement in the vehicle's environmental performance. Equation XX shows how the weight reduction target should be calculated, according to Broch et al. (2015). EIPr and EIPa stand for the environmental impact for the production of 1 kg of reference and alternative material, respectively. While the EIRVlc value represents the reduction of the environmental impact per km over an assumed running distance in km for a weight reduction of 1 kg. The next section addresses how to determine whether a target value is acceptable or not based on LCA results.

$$w_{rel} = \frac{EIP_a - EIP_r}{EIP_a + EIRV_{LC}}$$

(**Equation 1)**

v. Operationalization

The LCE methodology presented by the Volkswagen Group consists in the analysis of LCA results and the derivation of the mentioned measurable technical targets. This method uses the analogy of a traffic light to classify the environmental performance of improvement measures. In this process, LCA results of the alternative design options are interpreted and their performance are derived into one of the three traffic light colours. Figure 8 shows an example of how different lightweight design options are classified. The red, yellow and green colours are assigned respectively to the design with the worst, intermediate and best environmental performances. This traffic light representation is chosen because it is an intuitive form for the communication of targets (Broch et al., 2015).

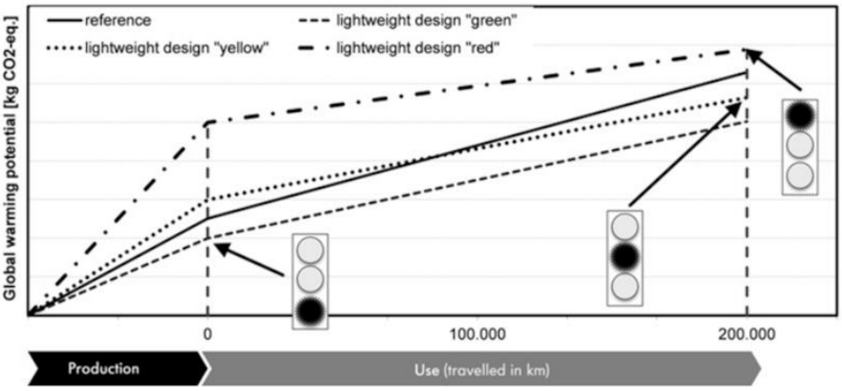


Figure 8. Derivation of light traffic lights from LCA results. Retrieved from (Broch et al., 2015).

The green traffic light is awarded to the alternative design that performs better than the reference right from the production. When the environmental benefits are realized during the use phase, after a certain amount of travelled km, the alternative is given the yellow light. The design that cannot show its environmental advantage in any of the life cycle stages is represented with the red traffic light.

This traffic light framework serves to define which technical targets produce an environmental advantage compared to the reference scenario. According to this criterion, the acceptable targets must define a yellow light or preferably a green light design scenario. In the example of the weight reduction target shown in equation 1, the traffic light criteria determine what weight reduction target is necessary to reach this acceptance. Figure 9 shows what is the necessary weight reduction for a hot stamped steel component in comparison to a cold stamped steel component, meaning that a typical weight reduction of 20% offers an environmental advantage already after production (Broch et al., 2015).

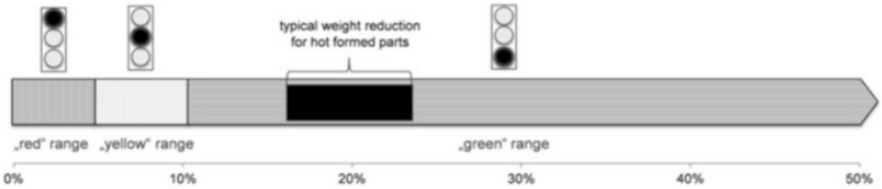


Figure 9. Necessary weight reduction for environmental advantage. Retrieved from (Broch et al., 2015).

vi. Participants

These technical targets are set and the objectives are tracked by the environmental officer. With the overarching goal of developing each model in such a way that has a better environmental performance than its predecessor the environmental officer is present in decisive boards and supports environmental decisions during the vehicle's development process (Broch et al., 2015).

3.2.3 AB VOLVO

During the nineties, Volvo decided to add the environment to its core values of quality and safety. This was viewed as an integral part of the company's strategy for achieving a competitive advantage. Since the beginning of the 1990s, Volvo's environmental strategy aimed at bringing changes in 3 main areas: (1) product design, based on reducing environmental impacts over the entire product life-cycle; (2) business development, aimed at providing products and solutions for the design of safer and more environmentally benign transportation systems; and (3) extrict procurement standards for supplier regarding environmental management and materials (Rowledge et al., 1999).

Volvo began research on LCA in 1989. This action aimed at minimizing the environmental effects of Volvo's operations by adopting a holistic approach to the environmental impact of its products through their entire life cycle (Louis et al., 1998). In 1990, this research led to the development of the Environmental Priority Strategies in design (EPS), in cooperation with the Swedish Environmental Institute and the Federation of Swedish Industries. Volvo's vision on EPS was to create an LCA tool that allows non-LCA practitioners, such as design engineers, to perform an environmental assessment of products and to communicate environmental improvements. EPS was developed as a software that enabled the aggregation of all the data coming from the inventory phase of an LCA to one single value, known as the Environmental Load Unit (ELU). In 1996, Volvo developed the SPINE database (Sustainable Product Information Network for the Environmental) that was integrated from there on into the EPS tool (Garcia et al., 2012). According to Wendel et al. (1999), Volvo LCA-EPS was extensively used for components when different alternatives are available such as in material selection processes (Chanaron, 2007). Damstrom (2006) is the last study that confirms that EPS is currently being used by engineers at Volvo. [Starting with the XC40 Recharge, Volvo Cars will disclose the average lifecycle carbon footprint of each new model.]

In 1997, Volvo started using Environmental Impact Analysis (EIA), that has also been known as Environmental Effect Analysis (EEA), which is an adaptation of the "Failure Mode Effect Analysis" to the environment (Garcia et al., 2012). This is a group method aimed at identifying important environmental aspects early in the product development phase. During meetings, a group of individuals with representative knowledge from various functionalities within the company should be able to identify every conceivable environmental aspect which a product or a component may have during its lifetime (Chanaron, 2007; Dahlstrom 2006). At the meeting, actions are determined and followed up from there on. According to Tingström et al. (2006), Volvo's teams prefer to use EEA early in the design process, as it is less time consuming than LCA-EPS and thus makes the environmental information available early enough to influence the environmentally relevant design decisions (Garcia et al., 2012). Tingström (2005) adds that EEA is more suitable to support a radical innovation, whereas LCA is preferable for incremental innovation (Garcia et al., 2012).

The next section serves to deepen the understanding about the LCA-EPS and the EIA methods.

3.2.3.1 Environmental Priority Strategies (EPS)

i. Goal

Environmental Priority Strategies (EPS) is a computerized tool developed to enable LCA to evaluate the environmental impact of components at every stage of their life-cycles. This tool was designed to assist designers in assessing the environmental impact value by means of Environmental Load Units (ELUs) of product designs and thus facilitating the comparison of alternative product configurations (Rowledge et al., 1999).

In 1998, Volvo's central LCA specialist group conducted around 60 LCAs. These LCAs were used for valuation or validation of one design aspect toward another (Rowledge et al., 1999). The EPS mainly supported designers in the choice of materials (Louis et al., 1999). According to Dahlström (2006), EPS is still an important tool to support decisions in the product development phase: *"The tool is used before the start of a project to identify environmental aspects as well as during and after a finished project to review initial decisions and build knowledge to future projects."*

In 1998, Volvo began using Environmental Product Declarations (EPD) to provide an easy-to-understand summary of vehicle's environmental profiles for customers. This way, Volvo's S80 became the first car with an EPD based on LCA results and certified by a third-party organization (Rowledge et al., 1999). At Volvo, EPDs are also a tool to validate environmental improvements of new vehicles in comparison with their predecessors (Dahlström, 2006).

ii. Scope

Louis et al. (1998) presented a case study that shows how designers at Volvo used the EPS system to compare the environmental profile of different car component designs. This study analyzes the environmental changes of using three alternative materials (Steel, SMS plastic composite and aluminium) in the tailgate panel structure. Figure 10, 11, 12 show simplified diagrams of the systems modelled by the designers.

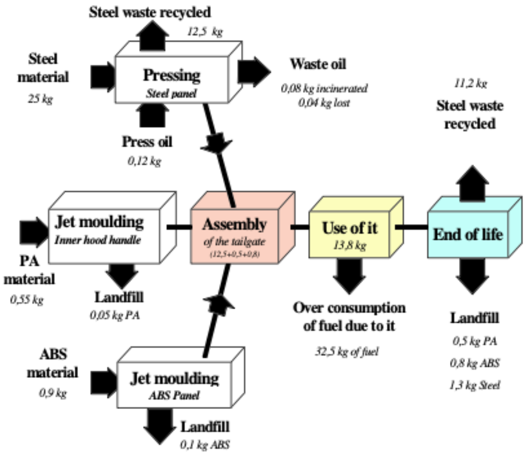


Figure 10. Diagram of the life cycle system of Steel panel. Retrieved from Louis et al. (1998).

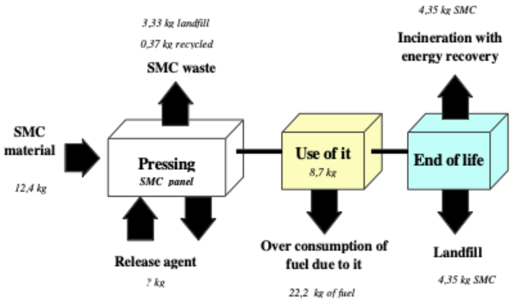


Figure 11. Diagram of the life cycle system of SMC panel. Retrieved from Louis et al. (1998).

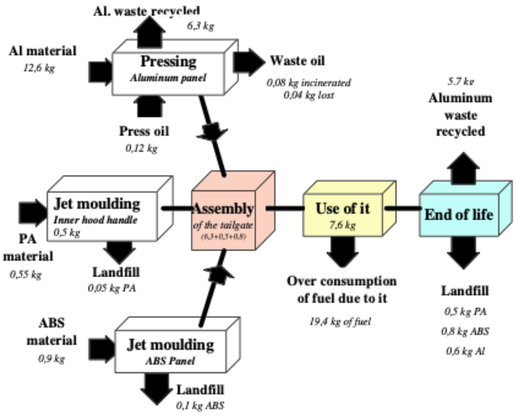


Figure 12. Diagram of the life cycle system of the Aluminium panel. Retrieved from Louis et al. (1998).

iii. Required resources

The EPS tool uses 2 sources of data, it requires data from a built-in database and data introduced by the user (designer). The EPS database was known as SPINE. This database was created to facilitate the exchange of LCA data and thus improving the operational implementation of LCA methods (Louis et al., 1999). Besides SPINE, EPS uses information gathered also from the material data system IMDS, as well as from intern specialists, environmental experts or suppliers (Dahlström, 2006).

The EPS method was designed to be performed by designers with no required expertise on LCA. The designer only introduces the amount of materials and components, and general data on processes and waste management. This method provides the designer with a list of environmental damage costs in the same way as ordinary costs are available for materials, processes and parts. According to Steen (2015): “the user of the EPS system shall be able to describe a product life cycle in terms of materials and processes for which ready-made weighted impacts assessments shall be available as indices”.

Steen (1999) said that the EPS system was developed with the ambition to be able to give an answer within the order of 5 minutes in the first phases of the product development. According to this author at this stage, several alternatives must be tested and a few are chosen for further evaluation. As the development process proceeds and the knowledge increases, designers demand deeper studies with more specific materials and processes, which also increase the time required to get answers. The EPS method also allows designers to introduce data from specific industrial plants and market regions.

iv. Sustainability coverage

During the development of the EPS tool, designers at Volvo argued that the tool needed to adopt the everyday language and thinking of designers. According to Steen (1999): “The flow charts used for mass and energy balances by many LCA practitioners at that time might be familiar to chemical engineers, but not to mechanical engineers, who prefer to think in terms of materials and processes.”

The result of the EPS impact assessment method is a single monetary value that measures societal environmental priorities by means of willingness to pay (WTP) assessment. This value is expressed in ELUs. One ELU represents an externality corresponding to one Euro environmental damage cost. According to Karlsson et. al. (1997): “these measures corresponds to what a fictive global society consisting of OECD-economies would be willing to pay today to avoid the changes in the environment caused by the product life cycle if it had to suffer from it itself”. It is important to state that the information in the ELU-value does not lie in the value itself, but in how it varies when the model input data changes and it is compared to other values (Steen, 1999).

This WTP for avoiding changes is used as the method to weight the different impact categories. The EPS method 2015 assesses impacts in five safeguards subjects: Ecosystem services (provisioning of resources, culture), access to water (irrigation, drinking water production), abiotic resources (land use and depletion of metals, oil, coal and gas, valued according to their availability or scarcity), biodiversity (species extinction) and human health (according to WHO Standards) (Steen, 2015; Rowledge et al., 1999). Earlier versions of the EPS did not include the access to water as an individual impact category. The ELU metric calculates the environmental impact on these categories. The ELUs are derived from market values and where no real market values exist, different pathways are used to estimate these costs. Emissions are evaluated by means of WTP for changes caused by the emissions on the environment, while raw material resources are evaluated by WTP for alternative renewable methods that produce comparable utility (Karlsson et al., 1997).

The process to define the ELU values is described using the Ecosystem services impact category as an example. The impacts on Ecosystem services is divided into two subcategories of indicators. The first subcategory represents the changes in the Ecosystem's provisioning capacity and consists in the following indicators: Crop growth capacity, production capacity for fruit & vegetables, wood growth capacity and fish & meat production capacity. The weighting factor of these impacts are expressed in ELUs. The ELU for the mentioned four indicators is measured as market prices, retrieved from the FAOSTAT database. This enables designers to account for the deterioration of Ecosystems services caused by the emissions and resource extraction of their product design. The second subcategory represents how changes in Ecosystems affect culture. Steen (1999) acknowledged the difficulties of describing changes in cultural and recreational value, as they are highly specific and qualitative in nature. In a later study this author proposed the indicator 'quality time', measured as the market value of outdoor recreational activities, such as skiing (Steen, 2015).

Steen (1999) was also aware of the limitations underlying the use of a single value that describes all environmental impacts. A single value, like the ELU can be considered as an oversimplification that misses to completely describe the complex interaction between environment and economic activities.

v. Operationalization

The EPS method was described in two publications, one about the general principles of the EPS system (Steen, 1999a) and one for the default impact assessment method (Steen, 1999b). The EPS system is considered part of the LCA methodology and it follows the ISO 14040/44 standards (Steen, 2015). However, in comparison to the LCA framework presented by Guinée et al. (2001), the EPS system presents an alternative way to conduct the impact assessment and the interpretation of results.

The operationalization of the EPS method at Volvo was described by Louis (1998). Similar to a common LCA, designers define the goal and scope of the study. In this phase is when the user identifies the functional unit and models the systems to compare. The systems, as shown in fig.8-9-10, are conceptual models that map the life cycle of the product in accordance with ISO 14040/44 standards. Once the inventory data is introduced into the models, the EPS software calculates and sums the ELUs that correspond to every unit process of the system. This leads to the valuation results.

The process to obtain the valuation results is explained with a simplified example. Suppose that a car component is manufactured from steel using JET moulding. This requires 3kg of steel. In the EPS database, the overall impact value for the production of the steel is represented as 2 ELU/kg. For the Jet moulding process there is an index of 0.2 ELU/kg. The total environmental impact value would thus be 3 kg*2 ELU/kg + 3 kg*0.2 ELU/kg = 3.78 ELU.

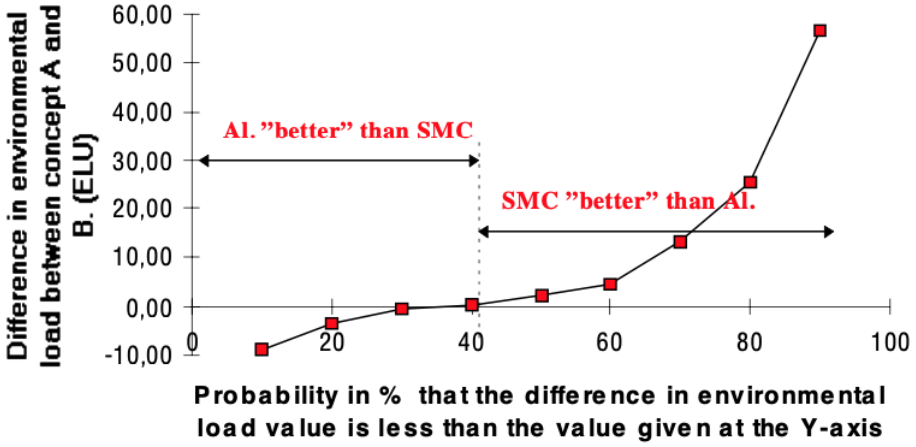


Figure 13. Graph of the difference in environmental load between concept A and B. Retrieved from Louis et al. (1998).

Afterwards, these results are validated through an uncertainty analysis. The EPS software has methods developed for the analysis of uncertainty, using estimates of identified uncertainty for individual input data. For that, the programme runs simulations that calculate the EPS result of a system using a log normal distribution of the inventory data, where the standard deviation of an input data is influenced by its uncertainty value. The uncertainty analysis results in a cumulative distribution that expresses the robustness of the EPS results. For instance, Figure 13 shows that there is 60% probability that the SMC material has a better environmental performance than aluminium, this means that when you vary different input data, roughly half of the time aluminium is better than SMC. Therefore, no relevant conclusions can be drawn from this. Finally, a sensitivity analysis allows the designer to observe the environmental impact as a function of the distance covered by the car.

vi. Participants

Internally, specialists in life-cycle analysis are responsible to support product development departments in the environmental impact assessment of product design. Each product development department has an environmental co-ordinator that facilitates the communication between engineers and LCA specialists (Rowledge et al., 1999). Workshops are arranged to communicate and share the environmental improvement measures implemented within the product development process (Dahlström, 2006).

EPS was developed for engineers, but it requires the support of a maintenance staff that provides the tool with the right data. Environmental experts are responsible to make all inventories and modelling of characterisation and weighting factors, which are needed for the database. This is why a right communication between engineers and LCA specialists has such a crucial role in the success of the EPS tool.

The development of EPS also influenced the expansion of partnerships with suppliers, external agencies and stakeholders (Rowledge et al., 1999). Volvo engaged its suppliers in achieving environmental improvements and involved them early in product development. They are expected to be experts in the environmental impact of their products, and use the same design guidelines as Volvo design engineers. As a result of this collaboration, suppliers provide insights and data that are used in LCAs internally (Rowledge et al., 1999). In 1995, Volvo started an environmental training programme intended at raising awareness of environmental issues among employees, dealers and suppliers. The program "Dialogue on the Environment" reached 79,000 employs and dealers, and a modified version "The Environmental Dialogue" was dedicated to suppliers and contractors. According to Volvo managers, the programs helped to understand and accept the relevance of sustainability to business success (Rowledge et al., 1999).

3.2.3.2 Environmental Impact Analysis (EIA)

i. Goal

The EIA method is based on the risk assessment method 'Failure Mode Effect Analysis' (FMEA). FMEA is a structured approach to discover potential quality and risk problems that may exist within the design of a product or process. EIA was designed to study environmental impacts in the same structured way (Tingström et al., 2006).

At Volvo, EIA aimed at making the environmental information readily available early enough in the product development process to be used to influence design decisions (Tingström et al., 2006; Garcia et al., 2012). The method assists product development teams in quick and effective assessment of environmental risks, clarifying the priority objectives and guiding them towards their fulfilment. According to Tingström et al. (2006): "EIA uses team dialogues, with the objective of making effective use of available knowledge and building upon the environmental requirements in laws, regulations and inputs from stakeholders".

This tool shows its highest potential when analysing a new product, whose quantitative environmental impacts are unknown (Lindahl et al., 2000). In these cases, the use of quantitative data would diminish the ability to have a meaningful positive contribution into the product's environmental performance. This is said because by the time enough quantitative data is available to do the analysis properly, it is generally too late to implement significant environmental improvements. Instead EIA is a qualitative method that gives prompt results able to be implemented early in the product development process. Although, its qualitative nature does not allow to use this method to make a comparison between two or more products.

Brambila-Macias et al. (2018) says that EIA has most frequently been used to evaluate new designs of Volvo's powertrains, aiming at minimizing the environmental impacts caused during the use phase. The author also claims that EIA has been used to evaluate the design of packaging materials.

ii. Scope

According to Lindahl et al. (2000), the definition of the right scope is crucial to ensure the quality of the EIA. The author presents a list of questions that ought to be answered before the functional unit of the system and the system boundaries are set: "What is to be examined and why? What function(s) does the examined product system/systems fulfil? What requirements concerning collected data have to be fulfilled in order to fulfil the goal of the analysis? What assumptions and limitations have to be introduced? What resources, regarding time, money and personnel are allocated for the analysis? How are the results to be presented, which are the target groups?". In an EIA, the functional unit and the system boundary is determined in the same way as it is done in LCA. Lindahl et al. (2000) provides guidelines by showing the examples of the most common system boundaries in terms of by-product systems, geographical boundaries, time and personnel.

There is not a single public scientific article that shows the utilization of EIA at Volvo. Therefore, it is not possible to show an example of the scope of this method in a real case study at the company. One of the reasons for the lack of a case study is that the results obtained by the EIA are not considered suitable for communication outside the company (Tingström et al., 2006).

iii. Required resources

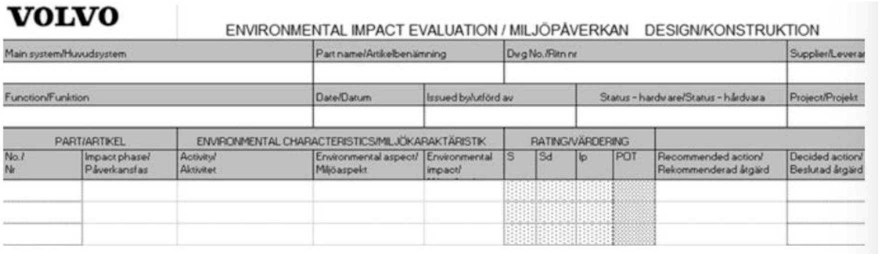
EIA, like FMEA, is a systematic working procedure performed in a group. Meaning that the knowledge and expertise of each member has a high influence in the success of the method, to promote effective evidence-based Eco-design measures. Volvo's 105-0005 standard defines how FMEA and its variant EIA must be performed during product development processes. This standard addresses the importance of choosing the right team of experts that have a thorough knowledge of systems and parts from a technical point of view, and of the method and working procedure.

The 105-005 standard states the importance of a correct and thorough collection of data prior to the team meeting, as this is absolutely decisive for the result. Guidelines for collection of the requisite data are described by the standard. This data on material content and processes is collected from several channels. These include functional analysis, lists of parts/components, material and function specifications, available data from suppliers, any regulatory and statutory requirements, results from market surveys and knowledge from previously made EIAs. Conclusions drawn from results and experiences of LCA studies, performed both externally and internally, are one of the main sources of environmental data, and when required marketing analyses performed by the Communication department can give valuable input about customer preference (Dahlström, 2006).

Interviews conducted to staff at Volvo show that designers prefer to use EIA over LCA in the early stages of product development. EIA is a method that uses already existent data and the knowledge of the participants. This allows the method to produce quick results that are readily available from the beginning, and it does not require to wait for any data and time intensive quantitative assessments (Tingström et al., 2006). Staff at Volvo also found it easier and faster to get started with EIA in comparison with LCA. The main reason for this is the similarity between EEA and FMEA, which they are more familiar with (Tingström et al., 2006).

iv. Sustainability coverage

Public scientific articles do not describe Volvo's working procedure to assess environmental effects via EIA, but there exists a consensus on how this is performed in the generic EIA. Therefore, the following text is not intended to present a complete picture of how Volvo evaluates these effects, because there is no data about the specific criteria they use. The EIA-form (figure 14) published in Brambila-Macias et al. (2018) shows evidence that Volvo followed the same framework proposed by Lindahl et al. (2000) (figure 15). This author proposes to qualitatively rate effects according to a number of criteria, resulting in an average score that points out what effects deserve more attention than others. Lindahl et al. (2000) presented different versions of this assessment method that mainly differ in the criteria chosen. However, the three criteria shown in the Volvo's form (S, Sd, Ip) do not completely correspond to the criteria given in any of those versions. This indicates that Volvo decided to customize these criteria.

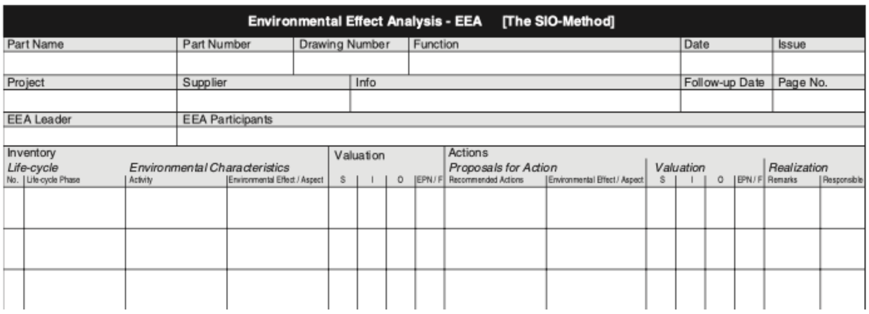

VOLVO
ENVIRONMENTAL IMPACT EVALUATION / MILJÖPÅVERKAN DESIGN/KONSTRUKTION

Main system/Huvudsystem	Part name/Artikelbenämning	Dwg No./Ritn nr	Supplier/Levera

Function/Funktion	Date/Datum	Issued by/utförd av	Status - hardware/Status - hårdvara	Project/Projekt

PART/ARTIKEL		ENVIRONMENTAL CHARACTERISTICS/MILJÖKARAKTÄRISTIK			RATING/VÄRDERING					
No./ Nr	Impact phase/ Påverkansfas	Activity/ Aktivitet	Environmental aspect/ Miljöaspekt	Environmental impact/	S	Sd	Ip	POT	Recommended action/ Rekommenderad åtgärd	Decided action/ Beslutad åtgärd

Figure 14. Volvo's Impact Evaluation form. Retrieved from Brambila-Macias et al. (2018).


Environmental Effect Analysis - EEA [The SIO-Method]

Part Name	Part Number	Drawing Number	Function	Date	Issue
Project	Supplier	Info		Follow-up Date	Page No.
EEA Leader	EEA Participants				

Inventory				Valuation				Actions							
Life-cycle		*Environmental Characteristics*						*Proposals for Action*		*Valuation*				*Realization*	
No.	Life-cycle Phase	Activity	Environmental Effect / Aspect	S	I	O	EPN / F	Recommended Actions	Environmental Effect / Aspect	S	I	O	EPN / F	Remarks	Responsible

Figure 15. Environmental Impact Analysis form of the SIO-Method. Retrieved from Lindahl et al. (2000).

According to Lindahl et al. (2000), the environmental assessment starts with the participants identifying the key activities associated with each stage of the product's life cycle. Then, they need to identify the environmental aspects of the activities. Effects refer to external and/or internal influences on the environment caused by the selected activities, such as consumption of resources, discharges into air, water and land, or generation of waste and by-products. Next, the team needs to identify the environmental impact associated with every aspect. As it is shown in figure 14, Volvo's EIA-form adds a column to identify these impacts. In EIA, environmental impacts refer to any change to the environment wholly or partially resulting from an environmental aspect. Some examples of environmental impacts are ozone depletion, resource depletion, and eutrophication. As discussed in Tingstroom et al. (2006) the environmental impacts evaluated are influenced by environmental requirements of authorities, and of internal and external bodies. These requirements can be endorsed by existing or future legislation and policies, or can respond to future market requirements and customer preferences.

The SIO 1-3 method is one of the techniques described by Lindahl et al. (2000) to assess the environmental impacts. This is considered the first method to be used for EIA and it is considered the foundation of many other assessment methods. The method consists in calculating an Environmental Priority Number (EPN) for every environmental impact. The EPN indicates how serious the impact is and it is defined as the sum of three variables: S, for controlling documents; I, for public image; and O, for environmental consequences. Every variable can take a value from 1 to 3, following the criteria shown in Lindahl et al., 2000. This method also includes a fourth variable called 'improvement possibility' (F), representing the effort in time, cost and technical resources needed to reduce the given environmental impact. After the evaluation, designers can place the results into an evaluation matrix (Figure 16), that determines which environmental impacts need to be addressed and which do not deserve special attention. The criteria for the interpretation of the evaluation matrix is defined by Lindahl et al. (2000).

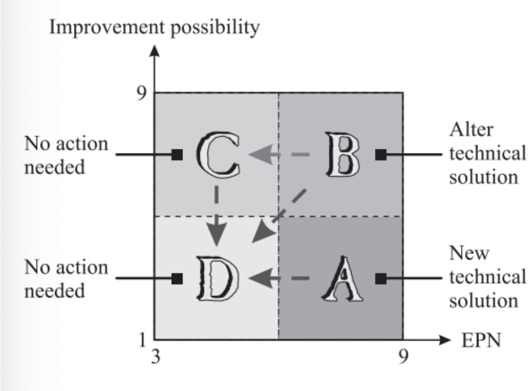
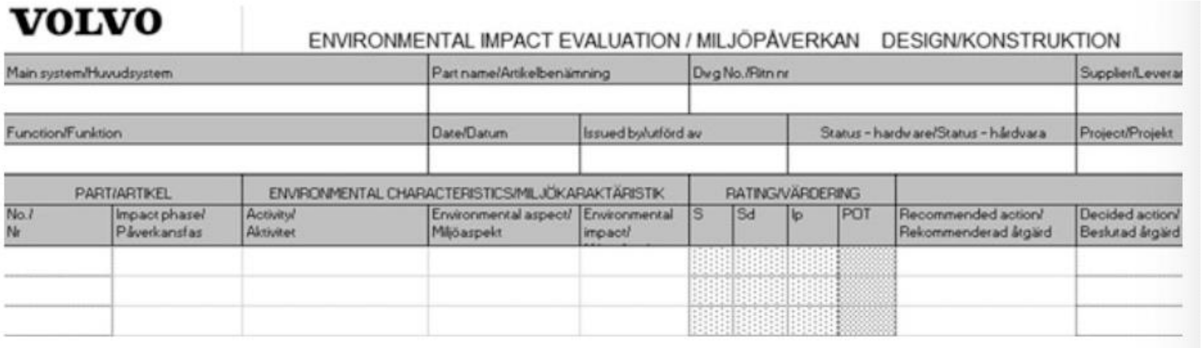


Figure 16. Evaluation matrix Retrieved from Lindahl et al. (2000).

v. Operationalization

As explained by Lindahl et al. (2000), the operationalisation of the EIA can be described as a linear process with the following steps: Preparations, inventory, analysis, implementation and follow-up. Figure 18, shows the work process flow chart for conducting the method. The first phase consists in defining the goal and scope, the composition of the team that participates in the EIA, and the kinds of environmental demands and regulations that will be included in the analysis.

Prior to the team meeting, as stated by the 105-005 standard, it is important that participants bring the necessary information at the time of the inventory. In the EIA inventory, the main environmental impacts of the products' life cycle are determined. This is done through the dialogue within the team, based on the knowledge within the group and the data collected beforehand. The inventory is divided into two steps. In the first step, a flow chart is drawn for the product system respecting the defined system boundaries. Secondly, data is connected to the different process units and this is reported in the EIA-form. Figure 17 shows a part of the EIA-form used by Volvo.



VOLVO

ENVIRONMENTAL IMPACT EVALUATION / MILJÖPÅVERKAN DESIGN/KONSTRUKTION

Main system/Huvudsystem	Part name/Artikelbenämning	Dwg No./Ritn nr	Supplier/Leverar

Function/Funktion	Date/Datum	Issued by/utförd av	Status - hardware/Status - hårdvara	Project/Projekt

PART/ARTIKEL		ENVIRONMENTAL CHARACTERISTICS/MILJÖKARAKTÄRISTIK			RATING/VÄRDERING					
No./ Nr	Impact phase/ Påverkansfas	Activity/ Aktivitet	Environmental aspect/ Miljöaspekt	Environmental impact/	S	Sd	Ip	POT	Recommended action/ Rekommenderad åtgärd	Decided action/ Beslutad åtgärd

Figure 17. Volvo's Impact Evaluation form. Retrieved from Brambila-Macias et al. (2018).

In the analysis, the assessment of environmental impacts is based on a relative evaluation of the intensity and seriousness of each effect, combined with the evaluation of the effort needed to reduce each effect. This evaluation method is described in section 'sustainability coverage' and its goal is to decide what environmental impacts deserve the most attention. In the second part of this phase known as 'proposals for action', the product development team submits a number of proposals for actions and the EIA team decides what proposals to choose. This is done following the method as the one used for the impact assessment, and thus actions are scored according to their ability to comply with regulations, to enhance public image and to be implemented cost efficiently. In this phase, actions that are able to address multiple environmental effects have a higher chance to be selected.

At Volvo, the results of the assessment of inventory of data are transformed into technical requirements called FKB, Function Requirement Description. This means that environmental aspects are translated into measurable technical targets that engineers are familiar with (Dahlström, 2006).

In the next phase, the proposed actions are implemented in the product's design. At Volvo, a person is designated in charge of each action to ensure that this is implemented in a successful way. During the implementation, it is considered relevant to document the possible problems that arise (Dahlström, 2006).

When the product development project is completed, a follow up of the outcomes of the study is made. In this phase the participants communicate their experiences on the implementation of the proposed actions, and evaluate the results of these actions to minimize the environmental effects previously identified in order to identify possible rebound effects that could compromise products environmental performance in an unexpected way (Lindahl et al., 2000).

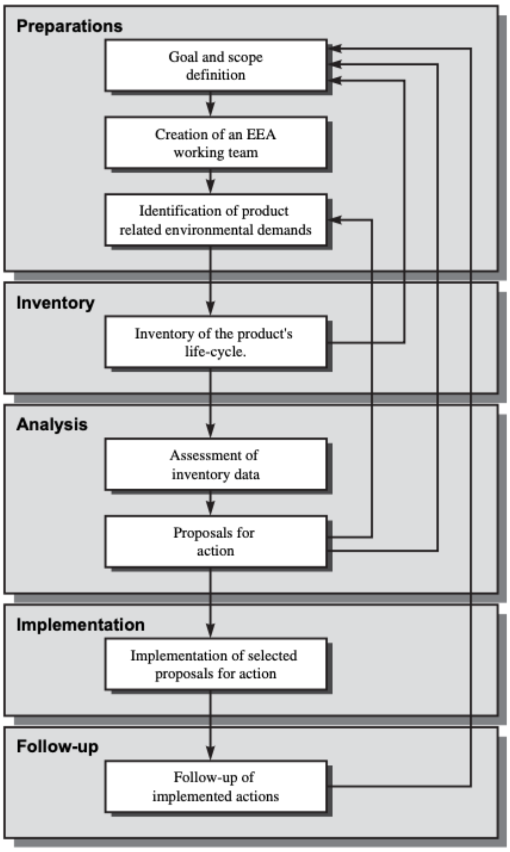


Figure 18. Environmental Impact Analysis process diagram. Retrieved from Tingström et al. (2006).

vi. Participants

At Volvo, the EIA team is composed of representatives from the product development, environmental department, production, aftermarket and purchasing. The team is led by a facilitator who has knowledge of the method and environmental aspects, and is responsible for preparing the meeting and filling in the forms (Brambila-Macias et al., 2018). According to Dahlström (2006), suppliers can also join the meetings if required.

3.3 Definition of screening criteria

This section serves to define the list of criteria used in the qualitative screening of the Eco-design tools. The screening allows to highlight the data collected in the previous phase, ‘understanding the tools’ and it enables to compare the tools’ strengths and weaknesses according to a list of criteria. For that, the list of criteria elaborates a theoretical framework that provides a complete picture of the tool’s operationalization within the companies’ product development processes. Following the method described in section 2.3., the next text reviews and argues the criteria selected.

Seven criteria are based on the screening method proposed by Broeren et al. (2018): Theoretical understanding (adapted to scientific consensus on indicators), System boundary consistency, transparency of indicators (adapted to two criteria impact categories and prioritization indicators), transparency of aggregation, user specialization and sustainability coverage.

Seven criteria are adapted from the thirteen criteria proposed by Pigosso et al. (2011). The author developed this list of criteria as a technique to classify Eco-design tools according to their functions, characteristics and application possibilities in the product development process. Instead of using the criteria to classify the tools, in this thesis, they are intended to provide relevant data about the function, characteristic and application of every tool. The following are the criteria adapted from Pigosso et al. (2011): Nature of the main goal, Nature of input data, Output mechanism, Origin knowledge area, Current development level, Demanded time for use and Information obtained about the tool.

The ‘Process design phases’ criteria is derived from the framework presented by Bovea et al. (2012). This criterion aims at comparing the process design phases in which the tools are involved. This information helps to understand the context in which the tools perform better. In the literature review it was seen that some of the tools are preferred to be used in parallel to the design process, while others are intended to be used in the beginning of it.

As mentioned in section 2.3, the screening method must cover the areas that are considered important for the designers. Lofthouse (2006), Birch (2012) and Brundage (2018) addressed this topic and their findings are covered in the screening. Lofthouse (2006) and Birch (2012) explained that designers require a tool with a useful output mechanism capable of delivering specific guidance and education. This is covered by the criteria adapted from Pigosso et al. (2011) mentioned before, ‘Output mechanism’. On the other hand, Brundage (2018) discussed that flow of information across different knowledge fields has a significant influence on the success of Eco-design practices. The ‘information flow’ criteria intends to compare to what extent the tools facilitate the cooperation between internal and external actors.

These mentioned criteria are not directly used to form our screening criteria, in the same way that their authors defined them. The reason for this is that they need to be adapted according to the subject they are intended to portray and to the information available about the subject. In the case of this thesis the subject is referred to the sample of tools. Therefore, the previous list of preliminary criteria serves as a foundation to develop the screening criteria, adapted to this thesis’ needs and limitations. The tables 2 shows and defines the criteria resulted from this adaptation process. The criteria were clustered into five main categories: Methodological approach, Goal & Scope, Operationalization and User aspects.

Criteria	Definition
Methodological approach	
Scientific consensus on indicators	Describe the degree of maturity of the indicators used by the methods. This criteria questions how well are these indicators understood and whether there exists scientific consensus on the mechanisms involved: - Internationally standardized: the indicators used by the method and the mechanisms behind them are well understood, and they are in accordance with the ISO 14040. - Lack of consensus: the indicators used by the method and the mechanisms behind them are not well enough understood.
Development level	Assess the current development level of the tool according to the actual application status: - Theoretical: there are just theoretical academic studies concerning the application of the tool - Experimental: the tool was already applied in case studies in pilot projects in order to validate them - Consolidated: the tool is already validated and applied regularly in the product development process of companies.
Origin Knowledge area	Describe the research area in which the tool was developed: - Eco-design/environmental management: technique/tool which origin is in the eco-design and/or environmental management field of scientific research, like techniques and tools to assess the environmental impact of products - Product development process: technique/tool which origin is in the product development field of research within companies
Goal & Scope	
Main goal	Describe the main question the tool aims to answer. Define the nature of the main goal: - Prescriptive: tools that present guidelines from a pre-established set of best practices for minimizing the environmental impact - Comparative: tools that aim to compare the environmental performance of products, concepts or design alternative to support internal decision-making processes - Prioritization: tools that aim to identify improvement potentials in the product performance and to prioritize improvement actions by means of the assessment of the most relevant environmental aspects - Management & Control: management and controlling of actions to improve the environmental performance of products
System boundary consistency	Evaluate whether the data utilized to derive the different indicators originates from assumptions that are consistent with the defined system boundary: - Consistent: System boundary in accordance with the ISO 14040. - Potential inconsistencies: The method does not ensure the consistency of the system boundary.
Sustainability coverage	Evaluates to what extent a tool measures all aspects of sustainability, focusing on the coverage in each of the three pillars: - Environment: The method provides a systematic procedure to assess product' or service's impact on the environment, considering a life cycle approach - Society: The method provides a systematic procedure to assess product' or service's impact on the society, considering a life cycle approach - Economy: The method provides a systematic procedure to assess product' or service's impact on the economy, considering a life cycle approach
Operationali	

zation	
Impact categories	Identify the impact categories used by the tool to derive the impact assessment results
Prioritization indicators	Identify the indicators used by the tool to prioritize improvement measures
Aggregation	Describe how the tool translates prioritization indicators or impact categories into a final aggregated result
Input data	Identify the type of input data and data sources required by the eco-design technique and tool: quantitative or qualitative.
Output mechanism	Identify the type of output data delivered by the eco-design technique/tool: report, graphs, tables, prioritisation or guidelines - Impact assessment: impact assessment of the product or service during its life cycle. - Prioritization: prioritization of the actions to improve the performance of the product or service. - Technical targets: technical targets that guide engineers and designers in the improvement of products' or services' performance. Targets are adapted to the language of the recipient, so he or she is able to monitor the progress.
Process design phases	According to Bovea et al. (2012), Eco-design tools can be integrated in multiple design phases (function description, requirements definition, generation of design alternatives, design alternative). Define how the tool is integrated in the process design phase: - In parallel: the tool is used continuously and iteratively in parallel to the product design phases - In a specific phase: users have expressed a preference over the benefits of using the tool in a particular phase
User aspects	
User specialization	Knowledge required by the user on material and energy inputs, product development and environmental impacts: - LCA expert: the user must have the knowledge to perform and report methodologically consistent (ISO 14040/44) LCAs. - Product expert: the user requires technical knowledge to understand and model all the processes involved in the product's or service's life cycle, including all the material and energy flows. - Other experts: the tool requires other types of knowledge than the ones covered by the mentioned experts.
Demanded time for users	Level of time demanded for users to get an answer from the given tool compared to the rest of tools in the sample. Estimated in relation to the information required to complete it
Information flow	Assess to what extent the tool facilitates the information flow from downstream stages or from other knowledge fields

Table 2. Definition of the Screening criteria.

3.4 Screening results

Once the criteria for the screening have been defined, the screening of the tools is conducted. This chapter presents the results of this screening (presented in table 3) and reflects on the conclusions drawn after comparing the results of every tool. The conclusions drawn are segmented according to the five categories presented in the previous chapter: Methodological approach, Goal & Scope, User aspects, Operationalization and Reference.

While section 3.2 aimed at structuring the information gathered from a number of scientific publications, the screening intends to create new knowledge by comparing the sample of tools over a list of criteria. The comparison serves to stress the capabilities and limitations of the tools, which are more difficult to appreciate when they are treated individually. Additionally, this exercise also serves as an experiment to observe how patterns are repeated for a number of tools, which can help to argue for instance that a certain tool property has a positive or negative correlation with a different property.

The screening presented in this chapter reflects an interpretation of the information extracted from the literature review. How the content of the screening is retrieved can be described using a few illustrative examples. In the case of the development level, most of the tools are considered consolidated. In particular, LCA at BMW is defined as consolidated due to the words of Traverso et al. (2015): "*The LCA according to the ISO 14040/44 is currently used at BMW Group as a supporting decision-making tool in the development process of the car to orient designers and engineers towards developing a car with a better environmental performance*". At VW, LCE is defined as a consolidated tool based on the statement of Broch et al. (2015): "*LCE is implemented in the environmental strategy of the Volkswagen Group and in the environmental objectives for technical development of the Volkswagen brand*". In contrast, LCSA at BMW is the only tool considered experimental and this is mainly because of the words of Tarne et al. (2017): "*So far, the LCSA framework has not been fully adopted at a company to assess the sustainability impacts of vehicles in order to support decisions for improvement measures aiming at the overall product sustainability impacts*".

Criteria	**BMW AG**		**VW AG**			**AB VOLVO**	
	LCA	**LCSA+PSB**	**LCA**	**DfX**	**LCE**	**LCA+EPS**	**EIA**
Methodological approach							
Scientific consensus on indicators	Internationally standardized (Traverso et al, 2015)	Lack of consensus on SLCA and LCC: insufficient guidance on indicator selection (Tarne et al., 2019)	Internationally standardized (Warsen et al., 2012)	Internationally standardized (Warsen et al., 2012)	Internationally standardized (Warsen et al., 2012)	Lack of consensus on utilizing monetary values to measure environmental impacts (Louis et al., 1998)	Lack of consensus: Indicators lack on specificity and they are subject to interpretation (Volvo's 105-005 standard)
Development level	Consolidated (Traverso et al, 2015)	Experimental (Tarne et al., 2019)	Consolidated (Warsen et al., 2012)	Consolidated (Warsen et al., 2012)	Consolidated (Broch et al., 2015)	Consolidated (Dahlström, 2006)	Consolidated (Brambila-Macias et al., 2018, Dahlström, 2006)
Origin Knowledge area	Environmental management (Traverso et al, 2015)	LCSA: Environmental management PSB: Product development process (Tarne et al., 2019)	Environmental management (Warsen et al., 2012)	Environmental management (Warsen et al., 2012)	Product development process (Broch et al., 2015)	LCA: Environmental management EPS: Product development process (Louis et al., 1998)	Product development process (Lindahl et al., 2000)

Goal & Scope							
Main goal	Comparative (Traverso et al, 2015)	LCSA: Comparative PSB: Prioritization (Tarne et al., 2019)	Comparative (Warsen et al., 2011b)	Comparative (Krinke et al., 2006; Warsen et al., 2011a)	Prioritization, Management & Control (Broch et al., 2015)	Comparative (Rowledge et al., 1999)	Prioritization, Management & Control (Lindahl et al., 2000)
System boundary consistency	Consistent (BMW Group, 2015)	Consistent: If LCA, LCC and SLCA have different system boundaries, practitioners must transparently report it (Tarne et al., 2019)	Consistent (Volkswagen AG, 2013)	Consistent: Focused on a smaller part of the product system (i.e. recycling, remanufacture)(Krinke et al., 2006; Warsen et al., 2011a)	Consistent (Broch et al., 2015)	Consistent (Louis et al., 1998)	Potential inconsistencies: High dependent on the team's knowledge and expertise: possible to overlook environmental risks (Brambila-Macias et al., 2018)
Sustainability coverage	Environment (Traverso et al, 2015)	Environment, Society and Economy (Tarne et al., 2019)	Environment (Warsen et al., 2012)	Environment (Warsen et al., 2012)	Environment (Warsen et al., 2012)	Environment (Louis et al., 1998)	Environment (Lindahl et al., 2000)
Operationalization							
Impact categories	Impact categories proposed by the CML method (BMW Group, 2015)	LCA: CML method LCC: Monetary values SLCA: Risk scores of social impacts (Tarne et al., 2019)	Based on the impact categories of the CML method: eutrophication, ozone depletion, photochemical ozone creation, global warming and acidification potential (Volkswagen AG, 2013)			EPS method 2015 impacts in five safeguards subjects: Ecosystem services, access to water, abiotic resources, biodiversity and human health (Steen, 2015)	-
Prioritization indicators	-	PBS: Specific questionnaire to calculate the WtP for sustainable solutions (Tarne et al., 2019)	-			-	EPN indicator is the sum of: S, controlling documents; I, public image; and O, environmental consequences. (Lindahl et al., 2000)
Aggregation	Although other impact categories are monitored as well, the main focus is on reducing global warming impacts (Traverso et al, 2015)	VIKOR method to calculate the criticality point for every dimension. Then these criticality points are weighted and result in the overall LCSA criticality points. Design options are prioritized based on the PSB. (Tarne et al., 2019)	-			The impacts are aggregated into a single monetary value, Environmental Load Unit (ELU) (Louis et al., 1998)	EPN value and F 'improvement possibility' indicate the priority of improvement action (Lindahl et al., 2000)
Input data	Quantitative data to model the processes/ flows involved using Gabi and ProBas.	Quantitative data: LCA: Process/flows through Gabi and Probas databases LCC: Not specific	Quantitative data to model the processes/ flows involved using Gabi 6, Gabi DfX, slimLCI and the VW SiCon process. (Volkswagen AG, 2013)		Quantitative LCA results (Broch et al., 2015)	Quantitative LCA results: SPINE database (Louis et al., 1998)	Quantitative and qualitative data from previous studies, and

	Measurable impact reduction targets are set to be monitored. (BMW Group, 2015)	data sources SLCA: Social Hotspot Database Qualitative data: PSB: WtP of customers, from surveys (Tarne et al., 2019)					participants' knowledge and experience (Dahlström, 2006)
Output format	Impact assessment (Traverso et al, 2015)	Impact assessment, Prioritization (Tarne et al., 2019)	Impact assessment (Volkswagen AG, 2013)	Impact assessment (Krinke et al., 2006; Warsen et al., 2011a)	Technical targets, Prioritization (Broch et al., 2015)	Impact assessment (Louis et al., 1998)	Technical targets, Prioritization (Lindahl et al., 2000)
Process design phases	-	-	In parallel (Warsen et al., 2012)	-	As early as possible in the design process (Broch et al., 2015)	In parallel (Dahlström, 2006)	As early as possible in the design process (Tingström, 2005)
User aspects							
User specialization	LCA expert (Traverso et al, 2015)	LCA expert, Product expert (Tarne et al., 2019)	LCA expert (Volkswagen AG, 2013)	LCA expert (Krinke et al., 2006; Warsen et al., 2011a)	LCA expert, Product expert (Broch et al., 2015)	Product expert (Louis et al., 1998; Steen, 2015)	EIA expert, Product expert (Tingström et al., 2006)
Demanded time for users	7 months (Estimation)	More than 7 months (Estimation)	6 weeks (Koffler et al., 2008)		Less than 7 months (Estimation)	7 months (Estimation)	Less than 7 months (Estimation)
Information flow	Increases external cooperation (Traverso et al, 2015)	LCSA: Increases external cooperation PSB: Systematic external dialogue (Tarne et al., 2019)	-	Increases external/ internal cooperation (Krinke et al., 2006; Warsen et al., 2011a)	Systematic internal dialogue (Broch et al., 2015)	Systematic internal dialogue (Rowledge et al., 1999; Dahlström, 2006)	Systematic internal/external dialogue (Brambila-Macias et al., 2018, Dahlström, 2006)

Table 3. Results of the Screening of the Eco-design tools selected from 3 automotive companies.

3.4.1 Methodological approach

The methodological approach category clusters three criteria that serve to compare the science behind the tools: Scientific consensus on indicators, development level and origin knowledge area. The first criteria show that the tools based on methodologically consistent LCAs are internationally standardized (in accordance with the ISO 14040). This demonstrates that there exists a scientific consensus on the indicators used by the method and the mechanisms involved in their impact assessments. In contrast with these standardized tools, there are three other tools that lack scientific consensus: (1) LCSA requires to combine three methods (LCA, SLCA and LCC), two of whom, SLCA and LCC have not been internationally standardized yet mainly because of a lack of sufficient guidance on indicator selection; (2) EPS lacks of scientific consensus on the utilization of economic values in order to measure environmental impacts, among the many limitations identified by Knights et al. (2013), economic environmental valuation methods do not achieve to comprehend the variety of human relations to nonhuman nature and they are sustained upon the questionable affirmation that money is a neutral measuring scale for people's preference; (3) EIA's category indicators are not in line with the definition presented by the ISO 14040 "quantifiable representation of an impact category", EIA indicators are used to qualitatively value the severity of environmental impacts and their lack of specificity makes them subject to interpretation. For this reason, EIA is not considered a reliable impact assessment tool and its operationalization must be combined with a methodologically consistent LCA that supports its results.

Regarding their development level, all of them are considered consolidated tools as they have been integrated in the company's product development processes for years. LCSA+PSB is the only experimental tool, meaning that has not being applied to real world applications within the company, but it has been tested in pilot projects in the company.

When comparing the origin of the tools, the screening shows that the majority of comparative tools come from the environmental management field. These are the tools that are based on the LCA operational handbook published by Guinée et al. (2001), and thus they are considered to originate from the environmental management field. The EPS is the only pure comparative tool that comes from the product development process field. The reason for this is that when Volvo created this tool, in collaboration with other institutions, there was not a standardized framework to conduct LCA yet. In response to the lack of an LCA framework, EPS was developed by experts in the product development process whose interest was to create a tool for engineers, designers and decision-makers. The rest of the tools PSB, LCE and EIA originated from product development processes of companies. These tools are the ones that analyse the environmental knowledge gained from LCA or other sources, in order to prioritize or/and monitor the actions to improve the products performance. This criterion shows that, for the sample of tools studied, comparative tools were in their majority developed by the environmental management field, while prioritization, and management and control tools originated from the product development field of research within companies.

3.4.2 Goal & Scope

The goal and scope category give a good overview of the main goal, system boundary consistency and sustainability coverage of the tools. The first criteria show that every company has at least one comparative and one prioritization tool. The comparative is essential to understand the environmental implications of their products. Meanwhile, prioritization tools interpret the results of comparative tools and translates them into technical requirements that the product design must fulfil. Apart from the comparative and prioritization, VW and Volvo also use tools to monitor and manage the progress of the improvement actions proposed. From this observation it can be deducted that these three types of methods can be used in combination to drive Eco-design practices in a business environment. First a comparative tool examines the biggest environmental impacts, the second prioritization tool explores the potential improvement possibilities and translates them in specific product design requirements, and lastly the management & control tool ensures that those requirements are met in the product development process. The interconnectivity between tools is further discussed in section 3.6, as it becomes an important result of this thesis.

Regarding the system boundary criteria, the screening shows that the majority of the tools are based on consistent system boundaries, since they are in line with the ISO 14040. It has to be said that in the case of LCSA, the method can be using results that are derived from different system boundaries. This can happen when the LCA, LCC and SLCA studies, combined in the LCSA, are based on different system boundaries. Different system boundaries can imply potential imbalance among the impacts assessed on the three sustainability pillars. However, this situation is not considered as an inconsistency in the case that the LCSA practitioner transparently discusses its implications. According to Kloepffer (2008) different life-cycle based methods for sustainability assessment should use the same functional, and consistent system boundaries, which are ideally identical.

In a similar line, DfX is considered having consistent system boundaries, despite the fact that this tool covers only a specific part of the product system. Narrowing down the scope of the study and not including all the relevant processes of the product's life cycle does not affect the consistency of the system boundary as long as it is clearly argued by the practitioner.

The case of EIA is different since its method does not provide a systematic procedure to ensure that all the relevant environmental risks are covered. According to Brambila-Macias et al. (2018), one of the main limitations of EIA is that the knowledge and experience of the meeting participants plays a big role in the result. This includes the possibility of overlooking environmental impacts and making the assessment dependent on previous knowledge and experience of users. This means that the method can be in conflict with the ISO 14001-2015 which states that "Within the defined scope of the environmental management system, the organization shall determine the environmental aspects of its activities, products and services that it can control and those that it can influence, and their associated environmental impacts, considering a life cycle perspective". In order to solve this problem, Brambila-Macias et al. (2018) presents a new method known as Environmental Screening (EnvS). EnvS in a checklist format ensures that the most important environmental risk factors are covered. This tool was tested by a reference group at Volvo Group and achieved to overcome the limitation presented by the EIA.

Concerning the sustainability coverage, the screening indicates that the majority of tools only aim at improving the environmental performance of the product. This is to be expected since this thesis focuses on the operationalization of Eco-design tools, which are by definition methods that address the environmental dimension and do not necessarily consider the rest of the sustainability pillars. However, it is surprising to discover that BMW AG is currently working on a decision-making tool that intends to include social and economic impacts together with the environmental impacts of their products.

3.4.3 Operationalization

The operationalization category intends to show the mechanisms behind the tools and to describe how these are operated in a product development context. The first two criteria offer a good overview of the impact categories and prioritization indicators used by every tool. On the other hand, the aggregation criteria serves to understand how the different tools translate prioritization indicators or impact categories into a final aggregated result. LCA at BMW AG does not aggregate the impact categories into a single indicator, but it is currently focusing on the reduction of one of the impact categories ‘climate change’, while still monitoring the influence on the rest of categories. In contrast with this, The idea of the LCSA proposed by BMW AG includes the possibility to aggregate different impact categories into a final criticality point, using the VIKOR method. In this method every element of the product’s life cycle is awarded with three criticality points, one per sustainability pillar. In the end, the three criticality points are aggregated once again into the LCSA criticality point, which describes the impact of every element on the three pillars. Finally, BMW AG also proposes a method that aggregates prioritization indicators into the so-called Product Sustainability Budget (PSB). The PSB determines the economic impact of every design alternative aimed at improving the sustainable performance of their products, by considering the costs connected to it but also the WtP of clients for more sustainable packages. This PSB result indicates which sustainable design alternative has the highest priority. For VW, there is not sufficient information to determine how their impact categories and prioritization indicators are aggregated. On the other hand, the screening shows that the EPS at Volvo uses a monetary value known as the ELU to aggregate the environmental impact categories and with the EIA prioritization indicators are aggregated into the known EPN value. These observations show that in a product development context companies often require tools that provide designers with a single aggregated value to base their decisions upon. The generic LCA does not offer this function, as environmental performance is described over a number of impact categories. However, in this section we have reviewed some of the techniques that companies use to aggregate several indicators into a single value.

The ‘input data’ criteria shows the type of data used by the tool, quantitative or qualitative, and their main sources. The ‘output format’ criteria gives a good overview of the type of results presented by every tool. It is seen that the output format is connected to the nature of the main goal, comparative tools result in impact assessments while prioritization and management & control tools lead to technical targets and to the prioritization of improvement measures.

Finally, the ‘process design phases’ criteria does not provide sufficient information about the tools used by BMW AG, but it does for the other two companies. VW AG expressed that LCA is conducted in parallel to the product development process while for LCE engineers expressed that it should be conducted as early as possible in the design process. A similar thing happens at Volvo where EPS is used iteratively in parallel to the product development process, but EIA is preferred as early as possible in the design process. The explanation for this is that, as stated by Tingström (2005), LCA is preferable for incremental innovation, whereas EIA is more suitable to support a radical innovation. Both LCA and EPS, at VW AG and at AB Volvo respectively, are able to support incremental innovation in parallel to the product development process. However, LCE and EIA, at VW AG and at AB Volvo respectively, are preferred in the beginning of the product development process because this is when radical innovations are more likely to happen. The later in this process radical innovations are more difficult to implement, because the product design is more detailed and less changes are tolerated.

3.4.4 User aspects

Since the majority of the tools required to conduct a methodologically consistent LCA and/ or interpret the LCA results, it is assumed that the user of the tool needs to be an LCA expert to get reliable results, unless the company denies this assumption. Volvo is the only company that used tools that were designed to be used by non LCA experts. For instance, the EPS is a comparative tool that was designed to be used by engineers, designers and decision-makers within the company. Similarly, EIA is a tool that does not require any LCA expert, but requires representatives from the product development, environmental department, production, aftermarket and purchasing.

Demanded time for every tool is estimated by comparing the time required to complete the LCI. The LCI is by far the most time-consuming part of every LCA. According to Koffler et al. (2008), in the automotive sector the maximum period of time required for an LCI is around seven months and the methodology developed by VW AG, known as VW slimLCI achieved to reduce this time to six weeks. Taking this as a reference point and assuming that BMW AG would publish an article if they achieved to shorten the time of their LCIs, it is estimated that BMW AG takes approximately seven months. Considering that the LCSA requires to gather data also for the social and economic pillars, it is fair to say that it requires more than seven months. According to Steen (1999) the EPS system was developed with the ambition to be able to give an answer within the order of five minutes in the first phases of the product development, although the author is aware that more time is required as soon as more specific processes are modelled. This is a special case because in the case of AB Volvo the EPS users were not responsible for the LCI, the LCI was performed by LCA experts who maintained the SPINE database and this database was accessed by the users to compare the environmental performance of their products. In line with our criteria to estimate the demanded time, AB Volvo did not publish the time required to conduct an LCI, and thus it is considered seven months. Finally, for the tools that do not require to conduct an LCI and they are based on already existing knowledge or expertise, the demanded time is assumed to be shorter than 6 months.

The majority of tools have proved that the communication between different knowledge fields is essential to drive Eco-design. As pointed out by Traverso et al. (2015)

about BMW AG getting closer to suppliers is necessary to get a deeper understanding of the environmental impacts caused by upstream processes. In the case of the VW SiCon project, it was seen that the knowledge of recycling plant operators was indispensable to develop a recycling technique capable of improving the ecological performance of their vehicle’s EoL (Krinke et al., 2006). These two are examples of the increase of external cooperation. An example of increase in internal cooperation is seen in Warsen et al. (2011a) where a collaboration within the company was required between the LCA practitioners and experts from the department of powertrain remanufacturing. There are also several tools that propose a systematic approach to facilitate cooperation. This is the example of the PSB proposed by Tarne et al. (2018c), which requires consulting customers, in order to measure their WtP for sustainability features. Another example of this is LCE at VW, this tool proposes a systematic way to communicate environmental improvements as technical targets that engineers can understand and implement to their designs. Finally, the EIA gathers experts from a wide range of fields that foster Eco-design during systematic dialogue meetings.

3.4.5 Conclusion

Screening the tools from a methodological approach highlighted a lack of scientific consensus and discrepancies that need to be acknowledged by the companies who intend to operate them. It is observed that some of the impact assessment techniques are not fully approved by the scientific community, such are the cases of LCSA and EPS. LCSA due to its current lack of guidance on indicator selection, and EPS because of the use of monetary values to assess environmental impacts. On the other hand, EIA presents discrepancies with the ISO 14040/44, since its lack of indicator specificity disables the method to provide reliable impact results. This finding does not pretend to underestimate the strengths of this tool, but it underlines the importance of using EIA in combination with a reliable impact assessment tool. Furthermore, it is observed a clear distinction in the origin of the tools. According to the screening, the majority of the comparative tools (aimed at quantifying the impacts of product on the environment) originated from the environmental management field, while the product development field has been in charge of developing tools that permit the implementation and management of the results coming from the comparative tools (i.e. LCA). This is observed as a demand of product developers for methods that allowed them to interpret these findings.

Looking at the goal of the tools it helped to understand how tools are part of a network where they complement each other. It was observed that the companies’ combined comparative, prioritization and management & control tools, with the purpose of ensuring the identification of impact hotspots, definition of action, and the implementation and evaluation of actions, respectively. On the other hand, the screening highlighted potential system boundary inconsistencies that can be solved through a transparent reporting, like in LCSA and DfX. Whereas EIA presents a more serious inconsistency issue related to its inability to ensure the coverage of all the relevant environmental risks, due to its high dependence on practitioners’ current knowledge.

The operationalization category provides practical information about how the tools function. One of the statements repeated by different companies is that prioritization tools (in charge of assisting in the definition of design requirements) must ideally provide results early enough in the product development process, because this is the time where the design has still space for changes (Broch et al., 2015).

Finally, the screening of user aspects have shown that the majority of the comparative tools have still need to be used by LCA experts. The only one that is operated by engineers or designers, the EPS, presents some methodological inconsistencies with the ISO 14040/44, which are understandable since the tool was created before the ISO standard was released. In terms of time intensity VW is the only company that developed a framework to reduce the time and increase the quality of their LCIs. And last but not least the screening showed unanimous view of the importance of facilitating a continuous flow of information among different knowledge fields and stakeholders.

3.5 Evolution of LCA within automotive companies

This new chapter presents the results of the historical contextualization of the publications analysed in this thesis. The previous section made possible to compare and understand how a sample of tools have been developed, adapted and operationalized in different automotive companies. Among other findings, this screening showed that over the years companies have adopted three life cycle approaches: EPS, LCA and LCSA. The contextualization of these methods aims at answering which were the reasons that influenced the companies to adopt the given life cycle approaches. By looking at the scientific developments on LCA of the last three decades and their correlation with companies' publications on life cycle approaches, it is possible to get an idea of where their methods stand, in terms of sophistication.

The following contextualization is based on the framework presented by Guinee et al. (2011). The author discussed the evolution of LCA from the conception and standardization of the method (1970-2000), to the so-called decade of elaboration (2000-2010). This analysis led to a forecast of where LCA was heading to, in the next decade (2010-2020). Figure 19 allows us to visualize in a timeline the main events in the evolution of LCA (based on Guinee et al. (2011) in comparison with issue date of the publications covered in this thesis. The events that occurred in the third decade were completed based on more recent publications, such as Guinee et al. (2016) and Zanni et al. (2020). The following text intends to explain the correlation between the developments on LCA and the life cycle approaches adopted by the three companies.

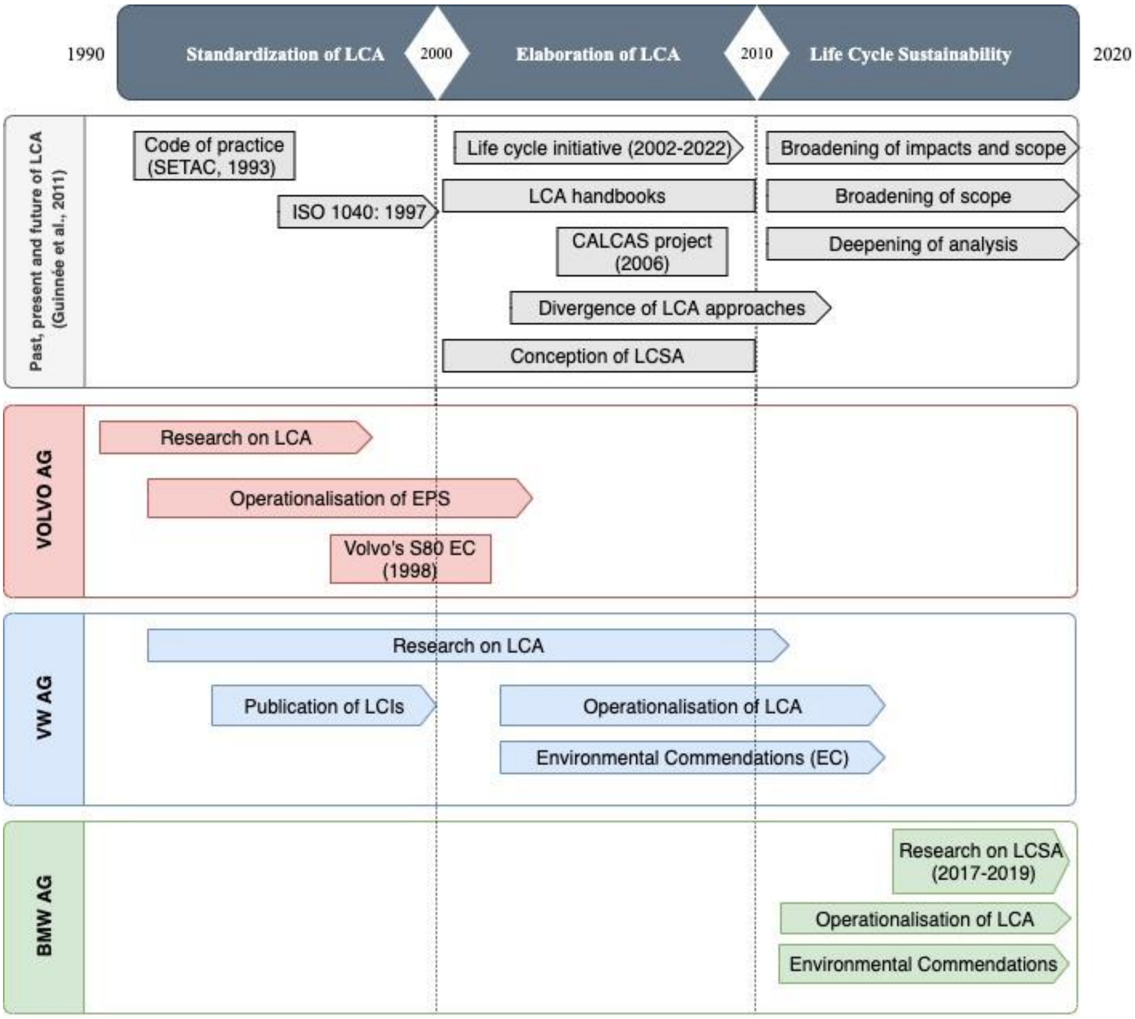


Figure 19. Historical contextualization of the studied publications. Publications discussing the operationalization of LCA in product development processes of AB Volvo, Volkswagen AG and BMW AG. The arrows (⇨) represent the beginning of an event in a timeframe according to public sources, but that continues in the future until an unknown year that is not clarified by available sources. The squares (▭) represent an event with a beginning and end in time according to public sources.

3.5.1 Decade of Standardization

From the three companies analysed above, Volvo was the first company to contribute to the development of an LCA methodology and also the first in integrating it in the product development process. Volvo began research on LCA as early as 1989, which led to the development of the EPS in 1990 in cooperation with the Swedish Environmental Institute and the Federation of Swedish Industries (Louis et al., 1998). The following years Volvo worked in the operationalization of the EPS tool and the result of this was the development of the SPINE database, integrated from there on into the tool (Garcia et al., 2012). In 1994, Ryding et al. (1995) presented the first EPS method, which was followed by an update in 1996 (Steen et al. 1996). Some years later, Karlsson (1997) and Louis et al. (1998) presented cases studies showing how designers at Volvo used the EPS system.

According to the framework proposed by Guinée et al. (2011), EPS method was conceived during the so-called 'Decade of Standardization' (1990-2000), which brought remarkable growth in both scientific and coordination activities towards the standardization of LCA. The Society of Environmental Toxicology and Chemistry (SETAC), and the ISO played key roles. SETAC adopted the role of the coordinator and led a group of experts that collaborated in the development and harmonization of the method. Meanwhile ISO worked on the standardization of methods and procedures. The coordination process of the SETAC led to the “Code of Practice” in 1993 and the ISO’s standardization work resulted in the ISO 14040 in 1996. There is no evidence implying that these events influenced the development of the EPS method. It has to be said that ISO did not intend to standardize LCA methods in detail, and thus provided space for variations in the method. Proof of this freedom was the new version of the EPS presented by Steen (1999), which described the EPS framework and terminology in accordance with the ISO 1040/43. However, even though the EPS method eventually converged into the ISO standard, it is interesting to discuss the origin of its particularities.

The EPS method was specifically designed to be operated by engineers, designers and decision-makers in a product development context. EPS presented a detailed method to conduct LCA that unlike the general methodological framework proposed by the ISO, this one had a clear direct application. The reason for this is that the EPS originated from the demand of the Swedish Industries, including Volvo, for a method that served to understand the environmental impacts of their products. This contrasts with the SETAC and ISO, whose goal was not to develop a ready to use tool, but they were more oriented towards building the foundation of LCA by filling a scientific and a standardization gap. As is normal, the lack of this scientific basis influenced the lack of scientific consensus on the impact assessment method proposed by the EPS. In particular, the mechanism that translates environmental impacts into economic values.

3.5.2 Decade of Elaboration

Similar to AB Volvo, The Volkswagen group began research on LCA in the early nineties. Between 1996-2000, the group published LCIs for various vehicles including the Golf III (Broch et al., 2015). However, the integration of LCA in their product development processes was not consolidated until the next decade. According to Guinée et al. (2011), this decade (2000-2010) is known as the ‘Decade of Elaboration’. During these years, the demand for LCA began increasing after receiving the coordinated support of governmental and scientific institutions. An example of this was the Life Cycle Initiative, an international Life Cycle Partnership between the United Nations Environmental Programme and the SETAC. LCA also grew in importance in environmental policy, highly influenced by the endorsement received by the European Commission who promoted its application among policy stakeholders. This was followed by the establishment of organizations like the European Platform on Life Cycle Assessment and other national LCA networks, aimed at enhancing the quality of the method and performing LCA studies for decision support in policy and business.

These years the method received special attention and the scientific community worked on the elaboration of a unified LCA method. This led to the publication of some LCA handbooks aimed at proposing operational guidelines based on the ISO standards (Guinee et al., 2001; Baumann et al., 2004; JRC et al., 2010). In this period of increased attention, LCA methodology was also questioned for a number of arising limitations. The previous decade of standardization settled its foundation but LCA is still subject to methodological limitations that compromise the robustness of its results, and limits its applicability in policy decision making. As stated by Guinée et al. (2011), in order to support policy decisions LCA had to face three main issues: (1) minimize the freedom of methodological choices, such as allocation decisions; (2) address the limitations of narrow-scope carbon footprint studies; (3) how to translate LCA results into real-world improvements, when the method is unable to analyse side-effects such as indirect land use or rebound effects. These and other limitations have been subject of study for the scientific community and there is not yet a clear consensuated answer to some of them.

After the first ISO standards were published, the Volkswagen group also started its contribution in the elaboration of the LCA methodology. Thiel et al. (1999) presented an integrated approach for assessing local and regional impacts within LCA. This study in which VW took part aimed to overcome the limitations of current global impact parameters that failed to address site dependent impacts, such as acidification or eutrophication. In 2008, Volkswagen presented the slimLCI, a technique that allowed them to reduce the time required for LCI, as well as improving the quality of the life cycle data (Koffler et al., 2008). In 2010, the group conducted a study aiming at improving the use phase modelling of vehicles, by using the so-called Fuel Reduction Value parameter (Koffler et al., 2010).

During this decade, VW started incorporating LCA in their product development processes. There are two substantial differences between the LCA approach adopted by VW and the EPS system developed by Volvo in the 1990s. Firstly, unlike the EPS, the newer LCA approach provides general guidelines for the operationalization and reporting of the results that are highly consensuated by the scientific community. This does not just allow LCA to influence internal decision making, but serves also to externally communicate the environmental performance of their products. EPS on the other hand is less suitable for this because it has not received sufficient consensus. Secondly, in comparison with EPS, LCA does not translate all the environmental impacts in a single unit, but considers essential to provide practitioners with a complete overview of all the environmental impacts, such as eutrophication, acidification, biodiversity, ecotoxicity and human toxicity, water use, etc. This feature provides LCA experts all the relevant information to interpret in a complete way the environmental performance of a product. However, it does add complexity to the single output value proposed by EPS.

3.5.3 Decade of Life Cycle Sustainability Analysis

During the next decade (2010-2020), BMW also started performing LCAs and publishing their findings in various vehicles (BMW Group, 2015; BMW Group, 2017; BMW Group, 2018; BMW Group, 2019a; BMW Group, 2019b). According to the scope of this thesis, the LCA method adopted by BMW did not include significant improvements in comparison to VW's approach. Nonetheless, BMW's main contribution focuses on the development of the LCSA methodology. As foreseen by Guinée et al. (2011), this decade is considered the 'Decade of Life Cycle Sustainability Analysis'.

With the ever-increasing demand of LCA in the previous decade, the limitations of the method also became more visible and the scientific community began to search for ways to counterbalance them. This led to the divergence of life cycle base methods and the development of new approaches, such as the dynamic LCA, spatially differentiated LCA, environmental input-output based LCA, LCC, SLCA and the more recent Ex-ante LCA. On this regard, Guinée et al. (2011) stated that there was a need for clarifying where these approaches differ or overlap and for determining which kind of questions should be addressed by each kind of approach. In 2006, this need was fulfilled by the CALCAS project which structured the roles of the varying field of LCA approaches and its findings pointed out the need for a framework for LCSA. According to Guinée et al. (2011), compared to environmental LCA the LCSA framework had three main differences: (1) broader impacts, from mainly environmental impacts to covering the 3 dimensions, environmental, economic and social; (2) broader scope, from product level questions to sector and economy level questions; (3) deepens the analysis, including more than technological relations, but physical, economic and behavioural relations.

Through the 2010s, the LCSA body of knowledge increased in both research conversation and practice standardization (Zanni et al., 2020). This substantially enhanced our understanding on how to shape the LCSA framework, but as stated by Guinee et al. (2016) there are still important issues that LCSA needs to overcome. The author stated as crucial the following 3 challenges, in accordance with the Guinée et al. (2011) framework: *Broader impacts:* definition of SLCA indicators; *Broader scope:* development of life cycle based approaches to evaluate future scenarios; *Deepening of analysis:* development of methods that deal with uncertainties and rebound effects.

In parallel to all these scientific developments and the increasing demand for LCSA, the company BMW AG expressed their intention to integrate the economic and social dimensions in addition to the environmental dimension covered by the current LCAs (Traverso et al. 2015). In line with this vision, BMW became one of the founding members of the Roundtable of Product Social Metrics. An ongoing project aimed to develop the *Handbook of Product Social Impact Assessment.* In 2019, BMW presented a LCSA framework aimed at improving the operationalization of LCSA in the product development context (Tarne et al., 2019). This framework achieved to address the first of the three challenges defined by Guinee et al.

(2016): definition of SLCA indicators. Tarne et al. (2019) presents a mechanism that allows companies to select social topics that they consider priority and serves to deduct their corresponding indicators. This study not just addressed the current limitations of LCSA, but also proposes a framework that covers the three pillars of sustainability and shows in a case study how its results can be integrated in the decision making of automotive product development processes.

As outlined by Guinee et al. (2016), and subsequently confirmed by Zanni et al. (2020), the scientific community has been focused on *broadening impacts*, while the rest of the challenges, *broader scope* and *deeper analysis,* have received significantly less attention. According to Gloria et al. (2017), Wu et al. (2017), Plevin (2016) and Kua (2017) represent the knowledge gained in this respect. LCSA should play a key role in the assessment of future scenarios. To do so LCSA can not rely on static models that neglect the evolutionary nature of the systems modelled. Dynamic modelling is required when analysing future scenarios and wanting to grasp the extreme complexity of systems under study. Wu et al. (2017) integrated dynamic modelling into the LCSA framework. This author proposed an agent-based modelling that not only uses indicators that evolve in time but also considers changes in the spatial dimension. The author recognizes that the framework presented is still simple and unrealistic, but it achieves to demonstrate the influence of temporal and spatial variations in a dynamic LCSA. On the other hand, Plevin (2016) and Kua (2017) propose alternative solutions to incorporate rebound effects in the LCSA framework. With the purpose of assessing unintended consequences caused by physical, economic and behavioural relations, such as market interactions, climate system feedback, changes in population and GDP, and technical learnings (Plevin, 2016).

3.5.4 Conclusion

With this chapter, it is concluded that the LCA approaches adopted by the different companies have evolved almost in parallel to the main scientific breakthroughs in the field. Volvo even got started with LCA while the scientific community was still settling its scientific foundations. The divergence of this method with respect to the modern LCA is found to be correlated with this lack of foundation, in combination with its origins. We can not forget that in contrast to the current LCA methods originated from the environmental management field, EPS has its origin in the product development field. This is the reason for the more practically-orientated nature of EPS compared to the science-oriented one of modern LCA. VW on the other hand contributed to the development of the methodology, during the elaboration years of LCA. The group published several scientific papers that indicate so, from researches addressing the LCA limitations at the time, to studies that aimed at enhancing the operationalization of LCA within the automotive sector. Once the scientific foundation of modern LCA was settled, Volkswagen Group started adopting this method within their product development processes, and discovered the necessity to speed LCI processes and enhance their quality. This demand resulted in the VW SlimLCI, a procedure to reduce the time required to perform LCIs as well as enhancing the quality of its results. Meanwhile BMW looks at the future and works towards the development of a tool that covers the three pillars of sustainability, as it is stated by the literature to be one of the next main challenges of LCA. In recent years, the Group has done research on how to enhance the operationalization of LCSA, by presenting guidelines for the selection of social indicators and demonstrating their applicability as well as reliability.

3.6 Systematic model to drive Eco-design

This last chapter presents the model that the three automotive companies seem to partially or fully follow, based on the literature review and its interpretation in section 3.4 and 3.5. It is necessary to clarify that the model does not indicate that all the companies perform all the processes identified by the model. Nonetheless, every process in the model has been observed in at least one of the three car makers. Additionally, due to a limited amount of data sources, this model can be overlooking processes that were not treated by the reviewed literature.

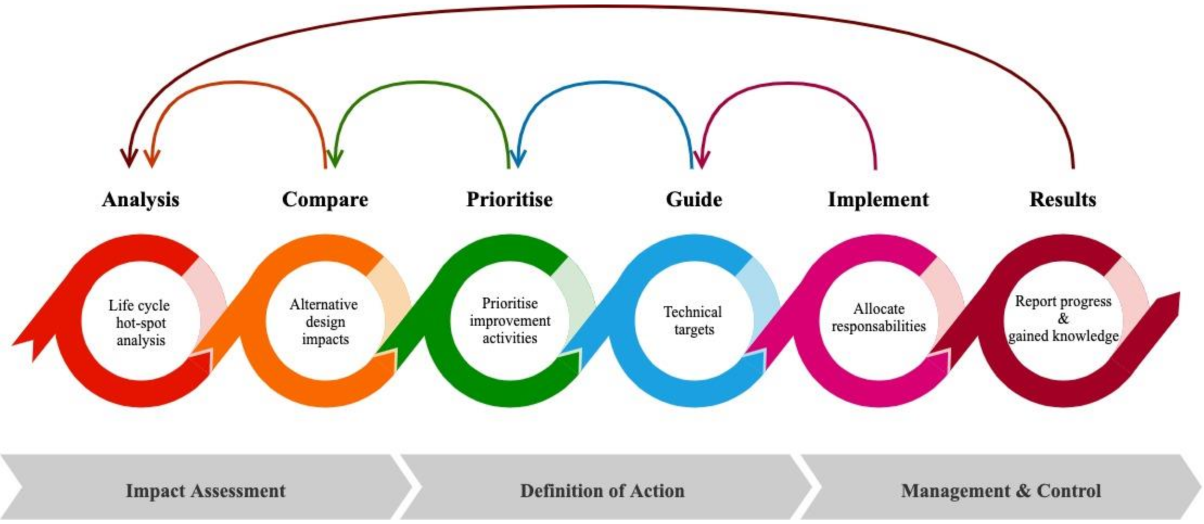


Figure 20. Representation of the 3 phases of the Eco-design model.

The model (illustrated in figure 20) presents a sequence of steps which if assisted by the right Eco-design tools, can lead to the successful implementation of Eco-design practices in a business environment. The model is divided into three main phases: (1) Impact Assessment, (2) Definition of Action and (3) Management & Control. These three phases correspond to the main goals of the tools observed in the previous chapters. According to the screening (section 3.4) the tools are designed to achieve one or more of these goals. This statement outlines that some of the tools are clearly defined within a certain phase of the model, while others can be used during different phases.

Figure 21, situates every tool within the three phases according to their goals. With the contextualization of the different life cycle approaches in section 3.5, it is justifiable to say that the tools EPS, LCA, DfX and LCSA belong to the same family of life cycle methods, that originated in different historical contexts. This is why the four tools are suitable to assist in the impact assessment phase, and thus they are considered replaceable. The analysis of them in section 3.2 and 3.4 can be used by practitioners to decide which of them fits their needs. DfX (i.e. design for recycling, design for remanufacture) is only considered suitable for the comparison process as DfX studies focus on a specific part of the product system and thus they are not meant to analyse hotspots. Furthermore, Environmental Impact Analysis (EIA) is considered a multifunctional tool and thus it is situated between two phases, definition of action and management & control.

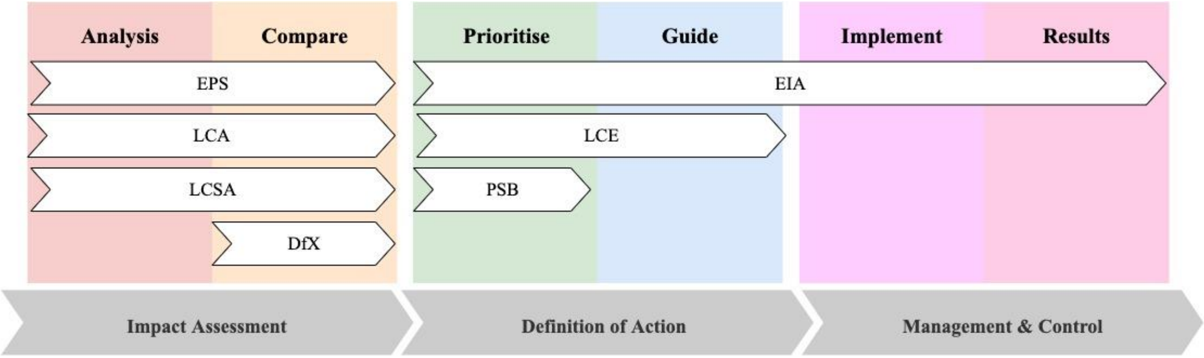


Figure 21. Representation of the Eco-design tools within the proposed Eco-design model.

The publications reviewed indicate that the three companies have adopted life cycle based approaches to assess the environmental impacts of their products. The tools that are used in this phase are the following: At BMW, Life Cycle Assessment (LCA) and Life Cycle Sustainability Assessment (LCSA); At VW, LCA and Design for X approach ; and at Volvo, Environmental Priority Strategies (EPS) and Environmental Impact Analysis (EIA). All these tools are based on quantitative methods except EIA which is based on a qualitative method that rely on the current knowledge of a team of specialists. As seen in the publications, these types of tools have two main functionalities within the product development processes, which were named in the model as 'Analysis' and 'Compare'. Analysis refers to the process of identification of hotspots along the life cycle stages. For instance, when assessing environmental impacts, hotspots indicate the processes with the highest share of impacts in one or more impact categories. Becoming aware of the hotspots allows practitioners to understand which part of the life cycle deserves more attention, and which stakeholders are involved in which impacts. Once the practitioners understand which processes can offer the highest environmental improvements, in the next step 'Compare' the impacts of alternative design are assessed. This is where practitioners study the consequences of new designs in the product's overall environmental performance. A clear example of this is the so-called DfX studies at VW, where the company studied the environmental impacts of new remanufacturing (Warsen et al., 2011a) and recycling processes (Krinke et al., 2006). These comparative life cycle methods help practitioners to make informed decisions to identify potential improvement activities, which in the next phase are translated into clearly defined technical targets.

In order to better understand the origin of the first two steps 'Analysis' and 'Comparison', it is helpful to observe the impact assessment phase as an analogy with the way optimization algorithms work. Optimization algorithm is a kind of algorithm that is used for optimization problems and aims at finding the optimal solution under given constraints. From this perspective impact assessment can be seen as the process of searching for an optimal solution that minimizes the impacts of a product on the environment. Within the theoretical framework of optimization algorithms, analysis plays the role of exploration and comparison the role of exploitation. In optimization algorithms, the exploration behaviour describes the capacity of an algorithm to find a global optimal solution within the search space. Whereas the exploitation refers to the ability of the algorithm to find the local optimal solution. Similarly, in the context of the model, the analysis explores the product system and indicates practitioners where the global optimal solutions are, while in the compare step those global optimal solutions are analysed to find actions that constitute the local optimal. To illustrate this with an example, in the first phase the practitioners may find out that the production of x material and the use phase provoke the half of the product's environmental impacts. This can be interpreted as the exploration phase where the practitioner searches around the whole life cycle stages, looking for the biggest improvement potential. Therefore, those two processes represent two possible candidates for the global optimum. In order to find the definitive optimal solution, in the 'compare' step practitioners have to find alternative designs (i.e. material selection, change in required energy source) that reduce the impacts of those processes, by performing comparative LCA studies. Using a similar analogy 'Analysis' lets the practitioners identify the diversity of problems, while the 'compare' intends to converge into a number of specific solutions.

The second phase of the model serves to decide what improvement actions are the most adequate and translates them into specific technical targets. In the 'Prioritize' step practitioners must score the priority of the potential improvement activities previously selected. Prioritization techniques have been explored by the three companies. Volvo with EIA intends to prioritize the improvement actions based on present and future environmental legislation, severity of impacts and public image consequences (Brambila-Macias et al., 2018). VW on the other hand presented Life Cycle Engineering (LCE), a method that enables practitioners to prioritize alternative designs of vehicles based on LCA results. Lastly, BMW proposes the Product Sustainability Budget (PSB), a technique that prioritizes actions based on a cost-benefit analysis that includes the study of consumers' WtP for sustainable vehicle options. All these techniques assist practitioners in the selection of a set of improvement actions that in the next step 'Guide' are translated into specific technical design targets. The 'Guide' step is derived from the tools EIA and LCE. Both of them provide techniques to define specific technical targets that allow engineers to implement changes that benefit vehicles' environmental performance. At VW, According to Broch et al. (2015): Technical targets must "use a language that is familiar to the recipient, such as the decision makers, engineers or designers in charge". Similarly at Volvo, with EIA the results from the qualitative assessment of the inventory data is transformed into technical design requirements, known as Function Requirement Description (FRD) (Dahlström, 2006). This way the techniques adopted by the automotive companies underline the importance of using technical targets as a communication tool to ensure that Eco-design is implemented in product development processes.

Once the technical targets are defined, the last phase 'Management & Control' ensures that these targets are implemented and the results of their implementation are reported. This phase is derived from the management and control mechanism shown by EIA. With the mechanism referred to its ability to assist in the supervision of the progress in the implementation of Eco-design activities. In EIA employees are designated in charge of every improvement action to ensure that this is implemented in a successful way (Dahlström, 2006). During the implementation, it is considered relevant to document the possible problems that arise and report the results when the project is completed. According to Lindahl et al. (2000), evaluating the results of the actions is crucial to identify possible rebound effects that could compromise products' environmental performance in an unexpected way. Last but not least, the results of Eco-design implementation shall be reported as a gained knowledge that can be applicable in future projects.

Chapter 4: Discussion

4.1 Comparison with similar studies

A previous tool comparison study, Bovea et al. 2012, successfully developed a classification of a variety of Eco-design tools offering companies guidelines for the selection of the right tools. This study provided an extensive review of Eco-design tools based on their theoretical capabilities, but missed to include the view of practitioners. In contrast with this, the present thesis has compared a sample of tools from the perspective of the practitioners or companies that adopted these tools and applied them in a product development context. This practical perspective allowed us to observe tools' strengths and limitations within a specific application (the ecological improvement of vehicles), which uncovered limitations only visible from a practical point of view. For instance, practitioners at VW and Volvo remarked the importance of utilizing methods that provide results early enough in the design process, and thus avoiding delays in relation with the product development process or coming up with design actions that are not applicable in advance stages of the process. This practical point of view also offers the opportunity to analyse what set of tools do the companies combine and learn from the symbiotic relationship between them. A clear example of this is the coexistence of EPS and EIA at Volvo. While the EPS is considered to foster incremental improvements, EIA had the role of driving innovative changes.

Dekoninck et al., 2016 provided an overview of the most common challenges faced by industry in the implementation of Eco-design. Some of the challenges proposed by this author were discussed in the present thesis. The author discussed "the difficulty to find the right balance between simplifying the LCA approach and the potential loss of accuracy, reliability and quality". This was highlighted during the screening that showed that alternative approaches like EPS and EIA presented conflicts with the ISO 14000, but nonetheless they offered benefits that overcome the common LCA in some aspects. The EPS stands out for its simplicity (made for engineers) and for its clear outcome expressed in a single unit, while the EIA stands out for its capacity to create collective knowledge.

However according to Dekoninck et al. 2016, the slow take-up of Eco-design in industry is not provoked by the constraints presented by Eco-design tools as much as it was expected. Instead the author pointed at the difficulties of internal and external collaboration as a more relevant bottleneck, something that was also stressed by the three companies studied in this thesis. The clearest example can be found at Volvo who provided courses to both employees and suppliers to raise this awareness, and demanded more transparency to their suppliers to make sure that are in accordance with environmental legislation and that they actively participate in the ecological improvement of the vehicles. Finally, Dekoninck et al., 2016 concluded that the management of Eco-design activities is the most frequently mentioned challenge by companies. Within this category the author highlighted the difficulty to select product requirements when there are trade-offs between environmental issues and other aspects such as costs. In the present thesis, we saw that this obstacle has been studied by researchers at BMW that came up with the PSB method, a systematic approach to prioritize Eco-design improvement actions based on a customer preference study.

Lamé et al. (2017) analysed the Eco-design practices in the French construction sector. In contrast with the situation in the automotive sector, so far, the construction sector in France has not adopted any other tool apart from LCA. The barriers for the implementation of Eco-design identified in this sector remind of the barriers that the automotive companies had to overcome in the last decades. Many of the barriers identified by Lamé et al. (2017) are visible in this thesis. Firstly, the difficulty to balance the environmental impact with other criteria, such as costs, functional aspects or social impacts. The automotive companies decided to combine LCA approaches with other techniques such as S-LCA, LCC, PSB or EIA that allow to balance environmental considerations of LCA with other criteria that stay out of the scope of this method. Secondly the author remarked that the cost of LCA was too high due to the man power required for LCIs. To minimize these costs VW developed a systematic procedure, known as slimLCI, capable of significantly reducing the time as well as increasing the quality of the data collection. Thirdly, the difficulty to compare design alternatives when multiple criteria need to be considered and no priorities are set. For this challenge we have observed that every automotive company has developed at least one prioritization method: BMW with LCSA and PSB, VW with the LCE and Volvo with EIA. Lastly the author concluded that practitioners presented difficulties to derive concrete actions from LCA results. From the present thesis and based on the model proposed in section 3.6, it is observed that the automotive companies have used LCA just as the starting point of the Eco-design implementation and further procedures are required, such as the definition of improvement actions, and management and control. Based on the Eco-design experience observed from the automotive industry, the construction sector is still at a very early stage and it needs to explore new tools that allow them to complement the limitations of the LCA approach. As it was demonstrated in this thesis, in a product development context LCA is simply one of the elements of our toolbox, but it can hardly be the only one.

As it was discussed in section 1.4, this thesis aimed at disclosing the mechanisms used in the automotive industry to implement Eco-design. A path that can serve as inspiration for other sectors with the same goal. However, the inspiration capacity can be constrained by the incapacity of other smaller sectors to emulate the mechanisms utilized by the automotive industry. It is also uncertain if the mechanisms used by the automotive companies are applicable to the rest of industries. These companies have been using LCA approaches as the main building block of their toolbox, but it is questionable whether such quantitative methods are suitable for every kind or size of companies. For instance, automotive companies design once a product, that besides some variations, it is mass-produced. This is not the case in the construction sector where every building is case specific and LCAs will have to become a routine procedure. The size of the company has also a big influence. While automotive companies are capable of investing resources and develop teams responsible to manage LCA studies, small and medium-sized companies do not have the resources to select the suitable tools and techniques in accordance with their needs. According to Pigosso et al. (2011), quantitative methods like LCA are more suitable for relatively large companies. Eco-design checklists are viewed as a suitable tool for small and medium-sized companies (Kiurski et al., 2017). Unfortunately, the present thesis did not cover this kind of tool because according to the literature it was not adopted by the chosen companies. It is known that Volvo has been using checklists (grey and black lists) to avoid the utilization of hazardous substances, but these tools cannot be considered Eco-design checklists because they are in conflict with the definition provided by the literature. In contrast with the definition of an Eco-design checklist (Kiurski et al., 2017), Volvo's checklists do not include a list of questions relating to the potential environmental impacts of products and do not suggest improvement options besides the sole selection of materials.

After this reflection, we can conclude that the Eco-design model proposed in this thesis will not be able to directly fulfil the needs of every company and sector, and thus the model requires to be adapted to every context. This adaptation includes the adoption of alternative tools, such as Eco-design checklists or other tools that fit best with the tools already used within the specific sector. Besides this adaptation process, it is believed that the model presented can serve as a starting point for companies that seek to integrate Eco-design in their product development processes. The steps proposed by the model are workable for a wide range of sectors when selecting the right tools or adapting them to their needs.

4.2 Methodological limitations

One can discuss the validity of the framework proposed in this thesis. As was mentioned earlier, the main objective of this framework was to learn from the comparison of Eco-design tools utilized by automotive companies, regarding their development, utilization and evolution within product development processes. With this purpose the framework presents a systematic procedure based upon information gathered from a literature review.

At first sight, it can be questionable whether a literature review is the best way to answer our question. In this context a literature review can be observed as the indirect way to explore the matter, somehow looking at the clues or traces that companies have left behind in their published documents. Whereas there can exist other more direct ways, such as surveys or interviews, that could shed more light on this issue. Perhaps they could provide us a more realistic picture of how these companies adopted and operated the tools. These research methods were discarded since capturing the unique reality of how tools shape Eco-design was left out of the scope of our study.

The chosen companies are the mainstream car producers in the world. Their dimension and complexity constraints our ability to fully understand the intertwin mechanisms that drive Eco-design internally. A single study of these characteristics (including internal surveys and interviews) can become a single thesis in itself. Additionally, this thesis aimed at going beyond a single company and comparing the behaviour of different entities. The comparative nature of this thesis provided an interesting framework to explore the diversity of paths that different companies have been taken to drive Eco-design. Analysing different subjects has special value in a novel field, such as the integration of Eco-design in companies, where there is still not a single established way to do things and the experimentation of tools and methods is key. After reflecting on these issues, it was decided to go for a literature review study, which narrows down our scope and facilitates the comparison of the strategies of different companies. It is acknowledged that analysing the literature does not enable us to capture the full picture of how companies drive towards Eco-design, but as mentioned before this is not the goal of the study. This thesis focused on analysing tools adopted by different companies, in order to individually study behaviours that when analysed as a whole help to build a theoretical model of how to stimulate Eco-design practices.

Undoubtedly the result of our framework is just one of the possible answers. As explained before this framework provides an interpretation of the reality based on a sample of data. However, despite being an interpretation, this study intends to ensure its accuracy, repeatability and reproducibility, transparently reporting the methodological choices and arguing the theory behind the results. The author is aware of the influence of its decisions and how the selection of alternative tools or another set of publications might lead us to different conclusions. The quality of data plays a key role in this.

Despite a systematic and extensive search of publications it was inevitable to end up lacking some information about the tools. Some of the documents published by the companies did not offer a complete picture of how the tools were operated. There could exist internal documents that we do not have access to or information that was simply never reported. For instance, this was the case for the EIA at Volvo. The official documents published by Volvo did not offer sufficient information on how the indicators were scored. This information was requested to the appropriate departments, but with no further result. In this case the information was retrieved from scientific publications that describe the methods, publications that did not take into consideration company's experiences, but they were still considered suitable for this research.

It is also possible to have a discussion about the usefulness of comparing the properties of the tools. As remarked by Volvo’s Decision Process, tools represent one of the many elements of the EMS of the company (Chanaron, J. J., 2007). There are other relevant factors, such as external players, environmental coordinators or environmental specialists that influence the design engineering departments and are thus out of the scope of the tools. Accordingly, we can question whether it is useful to do research on the comparison of tools in order to enhance our ability to drive Eco-design, or in contrast are other factors inside or outside the EMS which push the sophistication of tools forward. Personally, I believe that a little bit of both. Comparative studies provide a unique framework to critique limitations that would be difficult to discuss without a reference point. Despite not having a theoretical background that supports this, the identification of such limitations is essential for the evolution of the tools, without wanting to evaluate its level of contribution. As it was stressed throughout this thesis, it is important that companies become aware of the limitations of the tools they are using.

Identifying its limitations does not necessarily undermine the quality of the method, quite the contrary, it can enhance the effectiveness of the decisions derived from their results. Not being aware of them or not understanding them can misleadingly make the practitioner believe that is taking the right decision. In order to avoid this, it is essential to understand what the tool is capable of, but most importantly what questions it is not able to answer. As seen in this thesis, the publications showed that companies have adopted LCA approaches as their main mechanism to assess the impacts of design alternatives. These approaches presented some specific limitations (lack of indicator consensus and system boundary inconsistency) that were discussed in section 3.4. In section 3.5 on the other hand, we discussed what are the challenges that LCA will have to overcome in the future. It is obvious to imagine which will be the benefits of broadening the impacts (coverage of the 3 pillars of sustainability) or deepening of the analysis (including uncertainties and rebound effects) in a product development context. Although, it is debatable whether the third challenge involving the development of dynamic LCAs has a place inside product development processes. It can be interesting to reflect on this point for a moment and try to understand the implications of dynamic LCA within automotive companies.

4.3 Future challenge of LCA within product development processes

The scientific community has repeatedly stressed its concern regarding the lack of dynamicity of LCA approaches. LCA approaches are expected to assist us in the definition of future policies, but to do so the methods need to be able to consider the evolutionary nature of our world and leave behind the static models that only allow us to understand the reality at a specific point in time. This is the challenge that dynamic LCA intends to overcome. The literature argues that Dynamic LCA will play a key role in the analysis of future scenarios. However, one might question its applicability within product development processes of for example automotive companies.

Will these companies ever have the ability to perform dynamic LCAs? I do not have the answer for this, but I deduct that the availability of dynamic data will be one of the main challenges. For instance, this would include data about the evolution of the natural resources required for the vehicle's life cycle, influenced by material scarcity, development of new technologies, economic trends, future policies and so on. Another important question we can ask ourselves is whether these companies will be considered responsible to take informed decisions that consider long term scenarios, and thus encouraging them to use dynamic LCAs. To answer this question, we should look at how long into the future are decisions going to have an impact. This involves the lifespan of the vehicle. Between 2000 and 2009 vehicles had a lifespan between 9 to 23 years (Oguchi and Fuse, 2015). To this time, we would have to add the period of time the vehicle will be produced. Therefore, it can be argued that decisions taken by vehicle designers will have an effect in the long term, and thus adoption of dynamic LCA can be justified. However, its introduction within product development processes might not be completely necessary. Perhaps dynamic LCAs will be considered out of the scope of manufacturing companies and its utilization will be delegated to other research organizations that will advise these companies on their long term visions. These are just some of the questions that automotive companies might ask themselves in the near future.

4.4 Future research recommendation

As observed in the previous section, choosing automotive companies as study subjects poses serious constraints that limit our capacity to fully understand what is going on in such complex and big companies. This thesis proposed a comparative framework that addressed the development, adoption and evolution of Eco-design tools within the automotive sector. Future researches could apply this same framework, but focused on a more accessible industry. Perhaps with smaller companies where product development processes are allocated to a more reduced number of people. In this context, the literature review loses its meaning but the framework will still be reproducible based on other sources of data, such as interviews or surveys.

Chapter 5: Conclusion

This thesis concludes that the extraction of insights from companies’ experience with Eco-design tools can provide valuable guidelines for the integration of Eco-design within organizations with no such experience. By the comparison of a set of tools adopted by three mainstream car makers, through a literature review, this present thesis offers guidelines for the development of new tools and for the construction of an Eco-design model where complementary tools can contribute to the completion of Eco-design practices. Looking at the goal and output mechanisms of the tools helped to understand that tools within the model must complete 3 key roles: Impact Assessment, Prioritization of actions and Management & Control. Every role was extracted from the experiences observed within the studied companies. It has to be said that each of the companies' vision on these roles is perceived as incomplete, meaning that the combination of every companies’ vision leads to a more comprehensive model.

When observing the LCA approaches adopted by companies, two extreme views are differentiated. On one side the EPS used at Volvo, a simplified LCA approach, that is capable of providing fast and easy to interpret results, and is operated by engineers and designers. The EPS proposes a single value (ELU) that points to the best alternative design. This avoids the complex interpretation process of a common LCA, a feature that facilitates its use within product development processes. However, a simplification of the diverse nature of environmental impacts compromises its scientific rigour. On the other side the current LCA, DfX or LCSA, considered more scientifically rigorous methods that widen the scope of environmental impacts, are significantly more time-consuming and their practitioners require specific knowledge on LCA. This observation highlights the dichotomy that is frequently presented between scientifically rigorous and easy to use decision-making tools. On the one hand, from an environmental management perspective, a diversity of impact categories allows us to enhance our comprehension of the damages on the environment and take better informed decisions, while from the product development point of view, it increases the complexity of the results and thus constraints the capacity of vehicle designers that as stated by Steen (1999) “had several thousand decisions to make each year”. The previous reflection leads to the conclusion that product development processes require a tool or a combination of tools that combines both worlds discussed. This includes a fast and easy to use tool, and a tool capable of providing scientifically accurate results to take informed decisions.

Based upon this and other findings the impact assessment phase should ensure three main requirements, which were not seem to be simultaneously met by any of the studied tools within companies: (1) Identify impact hotspots and compare alternative designs in a scientifically rigorous manner (in accordance with ISO 14000/44); (2) Systematic interpretation of LCA results that allow engineers and designers to consult the social, environmental and economic impacts of their decisions, as a natural and iterative process along the design stage of the product; (3) The speed of the impact assessment should be in line with the timeframe of the product development process, in order to avoid that sustainable improvements are no longer workable given the late stage of the design process. This impact assessment should later lead to the definition of improvement actions which is supported by a second group of tools.

It is surprising to observe that every company studied has adopted or developed a tool with the purpose to turn impact assessment results into tangible design requirements. An observation that remarks the existing gap between the assessment of a product's sustainable performance and the complex task required to come up with actions that find the right balance of the possible trade-offs. This task was entirely or partially allocated to LCE at VW, PSB at BMW and EIA at Volvo. Based on the intrinsic mechanism of the tools and experiences of their practitioners, the following are the 3 requirements new tools should meet: (1) capacity to share information among different knowledge fields through team dialogues that allows to create collective knowledge and agree upon potential improvement actions; (2) prioritize improvement actions balancing multiple criteria including costs, technological limitations, willingness-to-pay of customers for sustainable solutions, functionality aspects, current and future legislation, and corporate image; (3) translate improvement actions into measurable technical targets, using a language that is familiar for designers and engineers that need to undertake these improvements.

Lastly, this thesis identified the so-called ‘management and control’ tools as an integral part of Eco-design. Inspired by the functioning of EIA at Volvo, these kind of tools are responsible to ensure that the improvement actions are included in the final product design, and for that to happen they should fulfil the following requirements: (1) Designate employees for the supervision of the progress in the implementation of improvements; (2) Share the possible obstacles that arise in order to find solutions; (3) Evaluate the results of the improvement actions to identify possible rebound effects that could compromise products' performance in an unexpected way; (4) Findings of the Eco-design implementation shall be reported to conform the knowledge foundation of future projects.

In conclusion, observing at these particular automotive companies, we remark that a quantitative impact assessment tool, such as LCA, is a crucial method but represents just one of the elements of the required toolbox. Within the explored business context, LCA is considered just the starting point towards Eco-design. The Eco-design process requires scientifically rigorous impact assessment methods to make informed decisions, but also requires tools that allow experts to reflect on impact results and enable them to explore improvement opportunities out of the LCA scope. From the observed experience, the LCA studies are conducted in a form that are too dependent on the product system of preceding versions of the product, which often limits radical innovation and rather results in small incremental improvement. In combination with LCA, systematic team dialogues between different knowledge fields shall contribute to the creation of collective knowledge that can help to find more innovative improvement actions, out of the scope of individuals with similar backgrounds.

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