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Eco-design Integration into New Product Development Processes: Comparison between LCA Software and CAD-integrated Tools

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ECO-DESIGN INTEGRATION INTO NEW PRODUCT DEVELOPMENT PROCESSES: COMPARISON BETWEEN LCA SOFTWARE AND CAD-INTEGRATED TOOLS

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TABLE OF CONTENTS

Page

APPENDICES

LIST OF TABLES

LIST OF FIGURES

Figure Page

ABSTRACT

Hernández Dalmau, Maria I. M.S., Purdue University, August 2015. Eco-design Integration into New Product Development Processes: Comparison between LCA Software and CAD-integrated Tools. Major Professors: Nathan W. Hartman & John W. Sutherland.

The constant growth of environmental concerns and in order to satisfy the increasing population demands, designers have started to integrate eco-design parameters in early design stages. The technological development that happened in the last decade has started to integrate LCA methods within CAD tools, allowing non-geometric data to be integrated in a typical geometrical model. The main research interest of this thesis is focused on the evaluation of the use of these emerging CAD tools, as tools capable to evaluate the futures environmental impacts of products and processes. This thesis studies through three comparative case studies if SolidWorks Sustainability as a CAD tool integrating LCA features, is an acceptable and feasible software to perform a real LCA. The LCA software used for the comparison is GaBi. Results from the analyses revealed that SolidWorks Sustainability works as a trade-off solution introducing sustainability features into product design. However, it does not provide an accurate and extensive analysis the same way a dedicated LCA does. Thus, CAD-integrated tools should be only used as comparative tools. Further research with different products, settings, and software will bring more precise conclusions about the accuracy of these CAD tools.

CHAPTER 1. INTRODUCTION

1.1 Background

After many years of insensitive exploitation of natural resources, the growth of environmental concerns together with an increasing collective awareness and a shift in environmental policy are impacting the way companies design products (Baumann, Boons, & Bragd, 2002; Maxwell & Van der Vorst, 2002). Greenhouse gas emissions in the U.S. are expected to grow 4% by 2020. The third largest contributor to the 4% increase is the industrial sector, after energy supply and transportation (United States Department of State, 2010). More and more products are needed to satisfy the population growth needs (Ramani et al., 2010) and it is therefore essential that designers integrate eco-design in early stages of product development (Hauschild, Wenzel, & Alting, 1999).

Environmental sustainability has to become one of the biggest tasks for society and the challenge is now to fulfill costumers' needs while accounting for product interactions with the environment (Choi, Nies, & Ramani, 2008; Luttropp & Lagerstedt, 1999; Maxwell & Van der Vorst, 2003). The holistic approach of considering environmental performance as well as institutional regulation and economic constrains, also offers a long-term business opportunity, improving the product quality and image, as well as enhancing the development of new markets (Pigosso, Rozenfeld, & McAloone, 2013).

Regarding environmental regulations, sustainable design is not only a potential tool to reduce environmental product taxes but also is a way to push the market towards a greener consumption pattern (Hauschild, Jeswiet, & Alting, 2005). To achieve these goals, eco-design is becoming an important and relevant topic in the future of engineering, where companies have started to understand that new products need to embody greener features and to consider all aspects of resource from the cradle to the grave. However, while important research continues on the effects of industrial processes on the environment, very little has been reported on integrating environmental requirements in early product development (De Silva, Jawahir, Dillon, & Russell, 2009). According to Baumann et al. (2002), the experts focused in the sustainable product field are not motivated in analyzing the usage and improvement of the already developed tools.

In the last decade, several tools have been introduced to the market to assess the environmental impacts of the life cycle of a product, being the life cycle assessment (LCA) methodology the main used technique. However, such tools are widely considered as being too broad for direct use in the product design process. In addition, these eco-design tools are known for being time-consuming and expert-dependent due to the product's extensive amount of required data. Many companies know about the potentials of these tools, unfortunately they are difficult to implement (Ostad-Ahmad-Ghorabi, Collado-Ruiz & Wimmer, 2009). Thus, product designers still lack a widespread and easy to use technique to integrate environmental requirements in their designs; they seek fast tools allowing quick results for eco-design assessments (Schiavone, Pierini, & Eckert, 2009). The growing technological development that happened in the preceding years has changed the traditional point of view of how products are designed. Computer aided design (CAD) data has been integrated with control information, introducing new simplified LCA methods (Jovanovic, 2009). Their goal is to perform a quick environmental analysis and to reduce the complexity of a complete LCA analysis (Morbidoni, Favi, & Germani, 2013). SolidWorks Sustainability is an example of CAD software that offers the possibility to perform an environmental analysis using GaBi's LCA software database. Now, such packages are supporting eco-product design but the assessment and evaluation of eco-design parameters in the CAD system is still debatable.

The main research interest of this thesis is focused on the evaluation of the use of CAD tools, as tools able to analyze the environmental impact of products. A comparative using LCA versus CAD software using simple products and a more complex mechanical product will be presented. Once the results are compared, an evaluation of the CAD tool as a substitute of an LCA analysis will be provided.

1.2 Statement of the Problem

Current CAD software tools are unable to correctly capture eco-design parameters during part-level geometric modeling, because the parameters used by current CAD systems do not adequately represent typical lifecycle analysis tools and assessments.

1.3 Research Question

How do the numerical results associated with the materials, manufacturing, use, transportation, and disposal of an LCA performed by a CAD software tool for a specific mechanical product, differ with respect to the results provided by a traditional LCA?

1.4 Significance

Up to now, environmental policies have relied on a reactive approach, focusing primarily on regulations that create limitations. These regulations are forcing companies to acknowledge the environmental impacts of their products; therefore, designers have to now incorporate design principles to reduce environmental impacts during all products' life cycles. Design decisions in early stages of product development can have substantial impacts on sustainability (Ramani et al. 2010), and firms are increasingly interested in achieving environmentally sensitive product designs due to the rising demand for eco-friendly products. Most experts involved in the industrial engineering community agree that the LCA methodology is the most widely used technique for evaluating the environmental profile of products (Millet, Bistagnino, Lanzavecchia, Camous, & Poldma, 2007). Time consuming analyses and product redesigns can be avoided using LCA information in early development stages. However, its limitations are also largely known (Millet et al., 2007):

- The LCA methodology can only be used for finished products.
- LCA is unsuitable as a comparison tool when two products have a different functionality.
- LCA demands extensive data acquisition.
- LCA is a costly, time consuming and complicated analysis.

There is actually no eco-design software able to gather all features of sustainable products, but when the work of a designer implicates the usage of computer design tools, it has been argued that new environmental tools should be integrated in this type of setting (Roche, Man, & Browne, 2001).

Thus, design tools integrating life cycle simulations for sustainability need to be developed (Ramani et al., 2010).

CAD software companies, such as Dassault Systems and Siemens PLM software, have recently begun to offer sustainable software packages: offering not only the design advantages of CAD software, but also providing instantaneous feedback on design choices using available LCA databases (Morbidoni et al., 2011). These tools allow designers to perform a screening or a simplified LCA in the early development process, with the aim of providing an easy-to-use application that helps designers to create sustainable products taking into consideration other standards such as product performance, product durability or total cost. These CAD tools are able to quantify the environmental impacts of a product, from the raw materials extraction to the end of life scenario. Some of the key offerings are flexible inputs for energy, alternative materials search, manufacturing region, transportations methods, or prediction of product's lifetime. Despite the CAD tools progress regarding LCA methods, the margin of error of the results compared to a traditional LCA is still a concern.

The main aim of this thesis is to provide a comparative study of an LCA and a simplified LCA using a CAD tool. The results will be used to determine the level of fidelity of these new tools, and to understand which parameters are taken into account by the software. Once the comparison is completed, it will be possible to understand if these new tools are a success, or whether these tools still present weaknesses that need to be fixed to perform a complete environmental analysis. It is intended that the comparative case study will contribute to a better understand the usage of specialized CAD software as an alternative to LCA.

1.5 Assumptions

The main assumptions that will be used in this thesis are:

- The LCA will be used as the most accurate environmental impact assessment tool. The performance of the CAD tool will be analyzed using that LCA report as reference.
- The LCA software databases are assumed to be complete and updated.
- In this thesis, the main purpose of using CAD software is to simplify the complexity of an LCA. Slightly different results due to this simplification are expected.
- The margin of error of SolidWorks Sustainability compared to GaBi is listed as +/- 20% in their specifications. A higher margin of error will consider SolidWorks Sustainability as unsuitable software to perform an LCA. The LCA methodology is a very flexible approach designed for a wide variety of industries and uncertainties are implicit to any LCA procedure (Intellect, 2012). The ISO 14040 does not specify a standard margin of error when comparing products. Other LCA software such as the Impact Estimator for Buildings considers a difference of 15% or less as being insignificant (Athena Impact Estimator for Buildings, 2014).

1.6 Limitations

The limitations relative to this thesis include:

- The availability of relevant data and its quality may limit the accuracy of the analyses. Inaccurate data will result in inaccurate results.

- The availability of processes and resources of the SolidWorks Sustainability library may constrain the environmental analysis.
- The assumptions made in the LCA, such as the selection of data sources or the choice of impact assessment category could be subject to bias.
- The LCA databases contain data only for the regions in which LCA is traditionally employed (Europe, North America and Japan) (Hauschild et al., 2005). The analyses in this thesis will simulate that the products and all the materials, processes, and resources are only from the available regions. Products from other regions cannot be analyzed.

1.7 Delimitations

This thesis will take into consideration the following delimitations:

- The results will be only an estimate of the environmental emissions of the analyzed products.
- Only four environmental impacts will be measured in the products' comparisons: the carbon footprints, acidification impacts, eutrophication impacts, and total energy.
- Only SolidWorks Sustainability CAD software will be used to perform the simplified LCA. The final results are specific to this software and the conclusions cannot be generalized to other CAD software.

1.8 Definitions of Key Terms

Eco-design – environmental management approach that integrates environmental issues into product development and related processes. It aims to minimize environmental impacts throughout the product's life cycle, without compromising other essential criteria such as performance, functionality, quality, and cost (Johansson, 2002; Weenen, 1995).

Computer-aided design (CAD) – "is a widely used tool for product design" (Tan & Vonderembse, 2006).

Life Cycle Assessment – "compilation and evaluation of the inputs, outputs and the potential environmental impacts of a product system throughout its life cycle" (ISO, 2006, p.2).

Impact category – "class representing environmental issues of concern to which life cycle inventory analysis results may be assigned" (ISO, 2006, p.5).

Sustainable product – product in which environmental, economical, and social aspects are given the same status as other traditional industrial values such as functionality or image (Baumann et al., 2002).

1.9 Chapter Summary

The introduction chapter provided fundamental information about the purpose and motivations of this thesis. The statement of the problem as well as the research question and significance of the research have been described. It outlined the main problem companies are dealing with in their implementation of eco-design. Some of the main assumptions, limitations and delimitations of the study are also identified. Finally, the main definitions related to the sustainable product field are defined. The next chapter contains the history of sustainability drivers in industry, the importance of environmental analysis, and the effective tools to address such impacts, including the advantages and disadvantages of current eco-design tools.

CHAPTER 2. LITERATURE REVIEW

The literature review chapter includes important concepts and previous research related to the implementation of eco-design into new product development (NPD) processes. Over the years, different methodologies and tools have been technically advanced to help companies study the environmental impacts of their products. Companies still hesitate using these tools due to implementation costs, complexity, and lack of integration of the eco-design tools into the organization enterprises. New CAD tools integrating LCA options are emerging in order to help companies integrate a sustainable approach to production. Through this approach, companies hope to create competitive products in terms of environmental sustainability. The next sections are specifically focused on analyzing current LCA tools limitations and on examining the future potential of the new CAD-integrated LCA tools.

2.1 Sustainability Drivers in Industry

In order to discuss the drivers of sustainability, one must first understand the term sustainability, an abstract concept centered in the economic, social, and environmental aspects of human development (Schönsleben, Vodicka, Bunse, & Ernst, 2010). Over the past decades, countries have enjoyed the benefits of industrialization for economic growth, but the lack of environmental consciousness during that growth is now bringing more deterioration to the environment. This environmental unconsciousness resulted in an increase of environmental regulation, putting companies under pressure to comply with legislation and consider environmental issues when designing new products (Maxwell & Vorst, 2003). However, firms can take advantage of the legislative hurdles and bring economical and social benefits to their companies (Gheorge & Ishii, 2007).

From an engineering perspective, eco-design methodologies have the potential to enhance current product design processes. Demands for more sustainable products are not only coming from the industry itself, but also the growing collective awareness' (Gheorge & Ishii, 2007). Environmental parameters in addition to structural, technological, and economical requirements must be taken into consideration in early product design. Luttropp and Lagerstedt (2006) graphically illustrated how the environment must be equally introduced into NPD processes (refer to Figure 2.1).

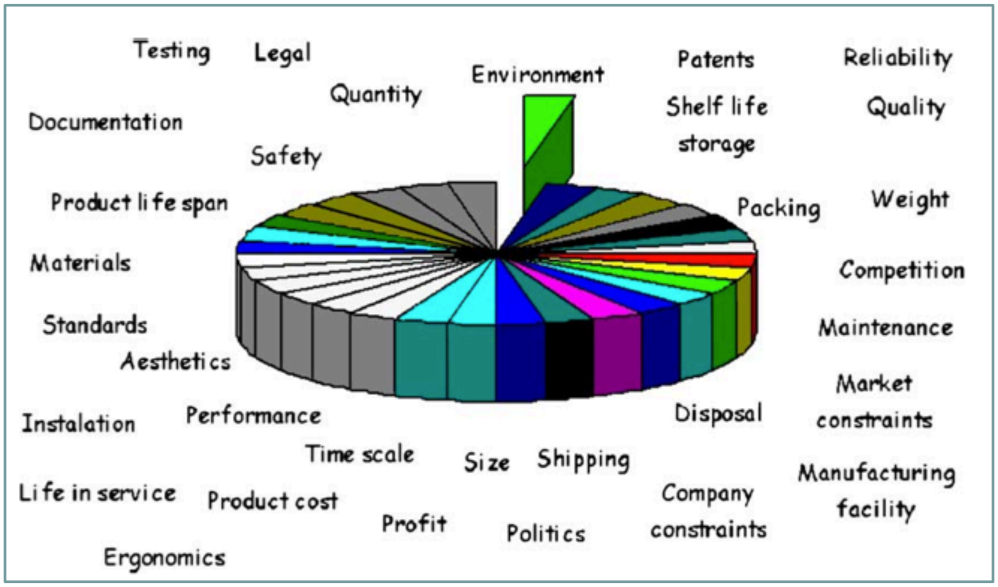
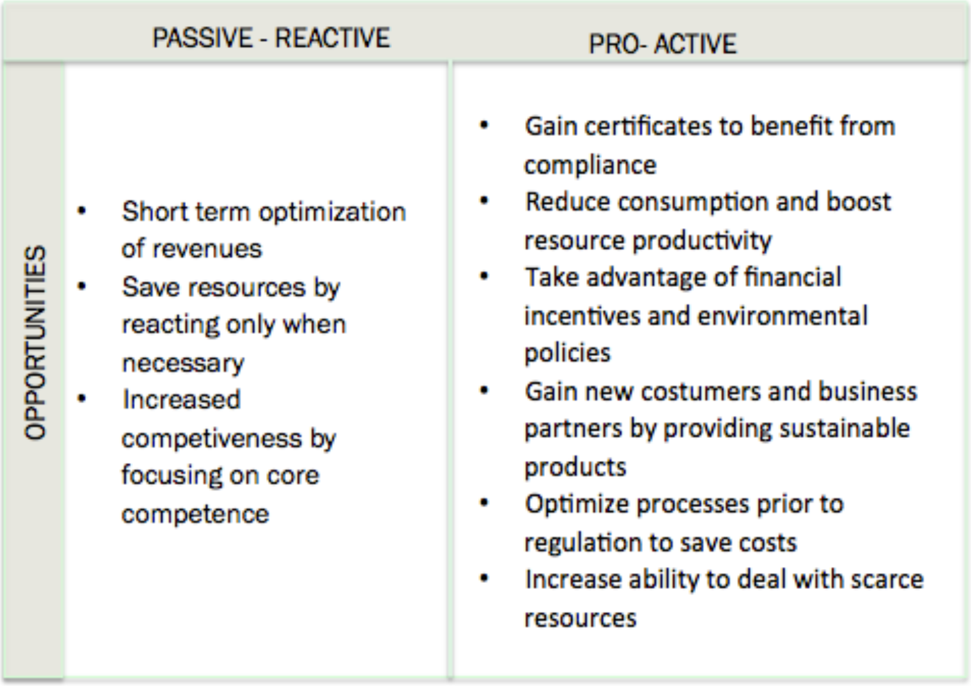


Figure 2-1: The Product Development 'cake' (Luttropp & Lagerstedt, 2006).

The economic drivers of sustainability are also an essential point to be taken into account. Positive environmental choices such as recycling or material reduction can bring economic benefits to companies. Firms can increase profits if they create a green image working towards environmental objectives, and become more influential.

In addition, eco-design can help avoiding financial liability due to environmental damage caused by products (Fitzgerald, Herrmann, Sandborn, Schmidt, & Gogoll, 2007). Companies who are able to recognize all these needs could create marketing opportunities and differentiate themselves from their competitors. Schönsleben et al. (2010) summarized the two different economic strategies towards sustainability: a passive-reactive strategy with low environmental commitment and a pro-active strategy with high environmental commitment (refer to Figure 2.2).



	PASSIVE - REACTIVE	PRO- ACTIVE
OPPORTUNITIES	• Short term optimization of revenues • Save resources by reacting only when necessary • Increased competiveness by focusing on core competence	• Gain certificates to benefit from compliance • Reduce consumption and boost resource productivity • Take advantage of financial incentives and environmental policies • Gain new costumers and business partners by providing sustainable products • Optimize processes prior to regulation to save costs • Increase ability to deal with scarce resources

Figure 2-2: Passive-reactive and pro-active strategies (Schönsleben et al., 2010).

A sustainable design approach can also be used to demonstrate the efforts towards social responsibility of businesses. Thus, companies should develop a marketing strategy and use a holistic approach in their design processes, facilitating the alignment of new sustainable strategies with the customers' needs (Baumann et al., 2002). To understand the basis of how the environmental impacts of products can be reduced, the main guidelines of eco-design implementation are presented in the following section.

2.2 Eco-design Implementation

Multiple meanings of the term eco-design, or sustainable product design, can be found in the literature. One of the simplest definitions describes eco-design as "the activity that integrates environmental aspects into product design and development" (ISO, 2002, p.2). The main purpose of eco-design is the minimization of the environmental impacts of the complete life cycle of products. The challenge of sustainable product designers is therefore to fulfill the costumers' need while maintaining the lowest environmental and economic cost possible. Companies need to evolve and start using multidisciplinary approaches to sustainability, and aesthetical and business objectives must meet the technical considerations in order to raise the product durability (Herrmann & Moeller, 2013).

Society is more conscious about issues like energy consumption or CO_2 emissions, and product developers cannot neglect their influence in the purchase decision (Gaha, Benamara, & Yannou, 2013). For this, sustainable product design takes into account the whole life cycle of a product (refer to Figure 2.3).

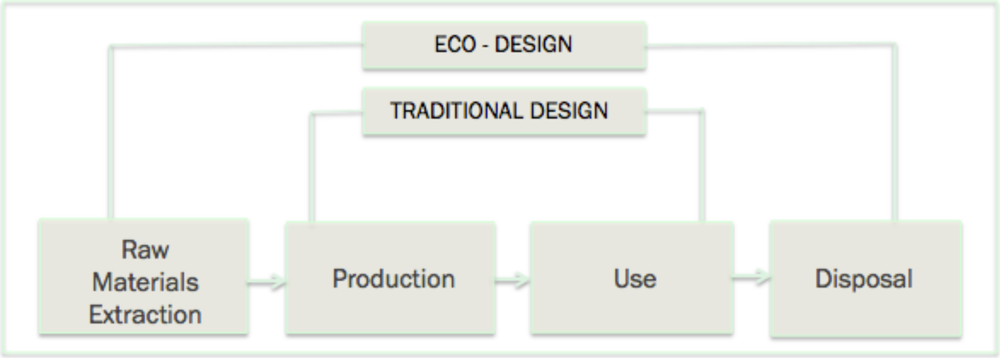


Figure 2-3: Eco-design, the wider picture (Knight & Jenkins, 2008).

2.2.1 Principal Gaps Regarding Eco-design

Kaebernick, Kara, and Sun (2003) emphasized that designers recognize that sustainability features should be integrated in their design. Most of the environmental assessments are carried out in the last stage of the development process. Moreover, despite the potential benefits of ecodesign, the integration of ecodesign has not reached all industries. This lack of eco-design implementation is often due to skepticism from industries, because they keep questioning its cost-effectiveness (Plouffe, Lanoie, Berneman, & Vernier, 2011). Baumann et al. (2002) affirmed that ecodesign has not been successfully integrated as it was expected the main reasons being due to the fact that many normative suggestions exist, there is too much tool development, and insignificant efforts in policy making are made (Baumann et al., 2002; Boks, 2006). Similarly, Pigosso et al. (2013) summarized the primary gaps regarding eco-design implementation as:

- Lack of systematization of existing eco-design practices: eco-design experts are more focused in developing new environmental methods than in improving the tool that already exist.

- Lack of integration between sustainable requirements and product development: the big majority of ecodesign tools consider the environmental aspects in an isolated way, without considering other products' requirements such as durability or weight (Bovea & Perez-Beliz, 2010).
- Lack of useful guidelines able to support companies and difficulties prioritizing the eco-design practices to be employed: difficulties to transform theoretical design rules into business. Customization of eco-design practices is crucial for companies in order to implement it (Boks & Stevels, 2007).

2.2.2 Advantages of Eco-design

Design plays an essential role within NPD processes. The life cycle of a product starts when the idea to create a product appears (Pigosso et al., 2013). Thus, environmental requirements must be introduced as soon as possible at the beginning of the product development. In fact, designers that use environmental evaluation in early stages of design have the main advantage of being able to make any required adjustments without economic consequences involved (Luttropp & Lagerstedt, 2006).

It is a fact that the introduction of environmental requirements requests an extra effort to companies, but it is also true that significant advantages can be derived: cost reduction, image improvement, and better relations with all the stakeholders, especially with with environmental authorities (Pigosso, Zanette, Filho, Ometto, & Rozenfeld, 2010; Plouffe et al., 2011). Thus, the integration of environmental aspects in design frameworks has become a prerequisite for companies to maintain their market position (Gaha et al., 2013).

Herrmann and Moeller (2013) also mentioned, "design involves not only the outward form-giving of the product but also the definition of a product's functionality, construction, user interfaces, ergonomics, materiality, and assembly" (p. 711).

Research by Kaebernick et al. (2003) described how the objectives for product decision-making have changed over the years. The three traditional key product design objectives are product performance and product and manufacturing costs. But during the last decade two new parameters have been added to the list: time to manufacture the product and total environmental performance. Balancing the five key design objectives against each other will bring an important advantage to the NPD process. Some researchers affirm that environmental requirements should acquire the same importance as all the traditional objectives in terms of design engineering (Kaebernick et al., 2003). The execution of eco-design may not be easy at the beginning, because the improvement of specific parameters might decrease the performance other parameters or features, but all the different aspects should be taken in to account (Poulikidou, 2012).

The goal is now to find an appropriate tool able to gather all these objectives, helping non-expert designers to design products in terms of the environment (Gaha et al., 2013).

2.3 Eco-design Tools

Over the years, sustainable product development is becoming a key subject in engineering design. Formal methods for the environmental assessment of products first emerged in a series of meetings organized by the Society for Environmental Toxicology and Chemistry (SETAC) in 1991 and 1993 (Ashby, 2012). Currently, an extensive range of techniques has been introduced by university researchers and by private sector developers (Le Pochat, Bertoluci, & Froelich, 2006). These techniques take into account the environmental constraints allowing the designer to be aware of the environmental performance of their products.

Different types of methods and tools range from general frameworks and recommendations to more specific and complex eco-design methodologies. Because of this variety, the outcome and the level of accuracy may differ significantly among these methods. Researchers affirmed that companies supporting an eco-design approach have more possibilities to be successful in the future (Plouffe et al., 2011). If product designers had the possibility to recognize the environmental impacts related to their products, they could make corresponding alterations or adjustments to their designs in order to improve the environmental features of the evaluated product. The existing techniques range from the simplest tools to more complex methods able to integrate a wider number of impacts. Depending on the function of each environmental tool, a classification can be made. Knight and Jenkins (2008) recognized three broad categories into which the different tools may be placed:

- Guidelines. These tools are easy to use and do not require experts. Guidelines do not tolerate an in-depth analysis but at least allow the user get a preview of the future environmental impacts of products. Even though these tools are not complicated to use, people with some minimum environmental knowledge should run them (Le Pochat et al., 2006).

- Checklists provide more detail than guidelines and are the easiest technique to use. Checklist normally consists of a list of questions, which firms can quickly and easily answer without the help of environmental experts.
- Analytical tools are the most complete tools in terms on environmental assessment. This type of tools provides more in-depth detail at specific stages of a product's life cycle. The main drawback for companies is that analytical tools require a lot of execution time and are expert dependent.

Bovea and Perez-Belis (2010) divided the different tools in three categories: qualitative, semi-quantitative, and quantitative tools (refer to Table 2.1).

Even though qualitative and semi-qualitative methods are not very reliable, they offer a quick and very straightforward analysis, and are especially beneficial when the environmental properties of the studied product are evident. The usage of quantitative methods generally appears when more specific environmental results are needed. Their main disadvantage is that they require a large amount of data (Bovea & Perez-Belis, 2010).

Table 2.1*: Eco-design Tool Classification.*

Qualitative techniques	**Semi-qualitative techniques**	**Quantitative techniques**
Checklists	Streamlined Life Cycle Assessment (SLCA)	LCA
Matrix Element Checklist	Environmentally Responsible Product	Environmental indicators: Oil Point Method (OPM)
MET matrix	Eco-design checklist method	Pre-LCA tool

Table 2.1 (continued).

Qualitative techniques	**Semi-qualitative techniques**	**Quantitative techniques**
Ten Golden Rules	Environmental Product Life Cycle Matrix (EPLC)	Streamlined LCA
	Product Investigation, Learning and Optimization Tool	Life Cycle Phases (LCP)
		Integrated development of Product & Process

To better understand the differences between some eco-design tools, Ramani et al. (2010) compared the design process and the type of tool: qualitative versus quantitative (refer to Figure 2.4). The graph clearly shows a linear trend stating that detailed designs are mostly obtained from quantitative tools.

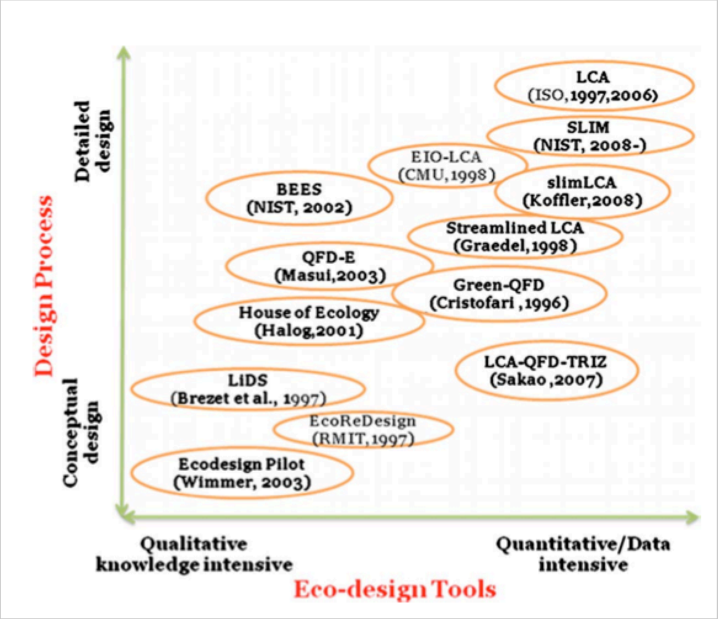


Figure 2-4: Eco-design tools comparison (Ramani et al., 2010).

2.3.1 The Life Cycle Assessment Technique

The most universal technique to evaluate the environmental performance of products is the life cycle assessment methodology. An LCA is defined as a "compilation and evaluation of the inputs, outputs and the potential environmental impacts of a product system throughout its life cycle" (ISO 14040, 2006, p.2).

Aside from environmental impacts improvement, product legislation compliance and to develop a positive image in the market are the most common uses of an LCA (Ashby, 2012). The LCA methodology allows the comparison of many parameters and processes of all the stages of an LCA, such as the used materials, the types of product distribution and delivery, or the end of life scenario (Millet et al., 2007). LCA data is of historical nature and therefore, it contains invaluable databases able to help designers to find the right path on sustainable product development.

According to the ISO 14040 standard, the four phases in which an LCA is carried out are (Figure 2.5):

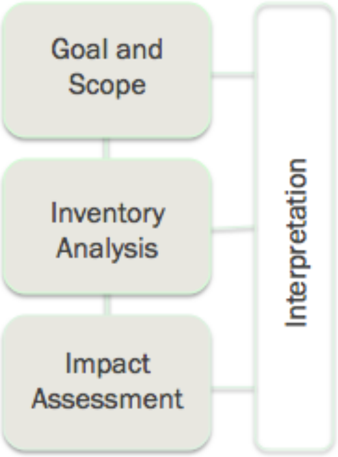


Figure 2-5: LCA phases.

- Goal and scope: in this section the purpose of the environmental analysis is declared. The system boundaries are also specified.
- Life cycle inventory analysis (LCI): section in which all the input and output data that enters and leaves is specified.
- Life cycle impact assessment (LCIA): the environmental impacts related to the LCI data are identified.
- Interpretation: discussion of the results from the previous phase. Conclusions and recommendations for future research are stated in this section.

Although an LCA is the most powerful technique for environmental evaluation, its limitations are widely identified. Probably the main limitation is that an LCA can only be successfully used for an entirely defined product. Many researchers have also agreed that low application rates of these techniques in companies exist. This low integration is a result of the execution difficulty of LCA tools as well as the required execution time, dependence on experts, and an overall lack of environmental knowledge (Bovea & Perez-Belis, 2010). Millet et al. (2007) clearly identified the LCA limitations and potential (refer to Figure 2.6).

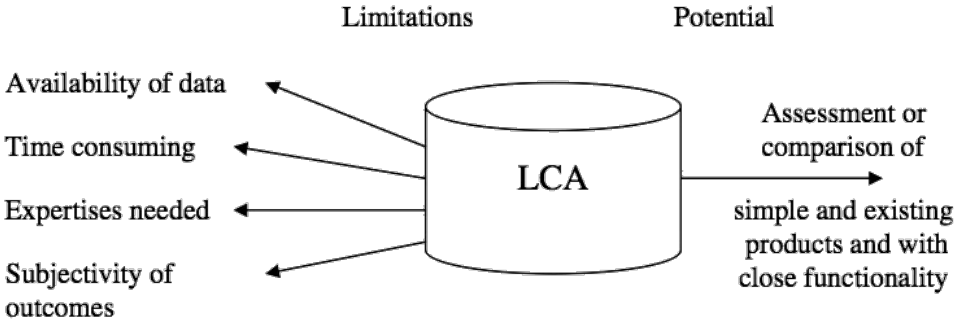


Figure 2-6: LCA Limitations and Potential (Millet et al., 2007).

Because of these limitations, LCA tools need to be contemplated as long-term techniques, especially useful to identify innovative concepts and main trends. In the interest of improving the short-term response of a product and in order to avoid the traditional LCA limitations, different simplified LCA methods have been developed.

2.3.2 LCA methods within CAD tools

According to Roche et al. (2001), “CAD tools represent an excellent opportunity for designer to extract, evaluate and prioritize the appropriate data automatically from a virtual prototype” (p. 20). The technological development that happened in the last decade has started to integrate LCA methods within CAD tools and the evolution of CAD systems has allowed non-geometric data to be integrated in a purely geometrical model (Gaha et al., 2013; Jovanovic, 2009). The main goal of a CAD software able to perform an LCA is to simplify and reduce the environmental analysis process without compromising the key features of a traditional LCA (Morbidoni et al., 2011).

Although the CAD phase is the last phase in the design process, the environmental impacts generated by the remaining choices are quite significant. Thus, the development of these CAD-LCA tools is essential (Gaha et al., 2013). The aim of the LCA-CAD tools is to assist the designer during the embodiment phase, integrating a set of computer-aided tools in a structured process, which “permits to simultaneously manage three key features of the product (shape, material, and production method) and to obtain the minimum environmental impacts” (Russo & Rizzi, 2014, p.2).

Thanks to this new integration, designers become aware of the consequences that each change in geometry, material or manufacturing process will produce on the environment (Russo & Rizzi, 2014).

Commercial CAD-LCA tools are essentially based on data exchange between the two different systems. But very few CAD applications for eco-design have been really implemented and are commercially available to designers (Gaha et al., 2013; Hatcher, Ijomah, & Windmill, 2001). Some examples of CAD software offering an environmental analysis are PTC Windchill LCA, EcoDesigner for SolidEdge and Autodesk Inventor, or SolidWorks Sustainability.

Most of these software packages are the result of some researchers' work, who have developed plug-ins to add the specific features of an LCA to the existing CAD software tools. For example in 2001, Roche was the first to undertake environmental analysis within CAD software, followed by Leibrecht, who in 2004 developed a plug-in suitable for Pro/engineer. Russo et al. (2014) represented the evolution of CAD tools for eco-design during the last decade (refer to Figure 2.7).

Morbidoni et al. (2011) claimed that in general, these new CAD-integrated tools offer the possibility for designers to develop an advanced approach, but errors derived from the simplification and lack of data on software libraries are still present.

Therefore, further study to compare and investigate if these new emerging tools meet the criteria to analyze the environmental requirements of products should be conducted.

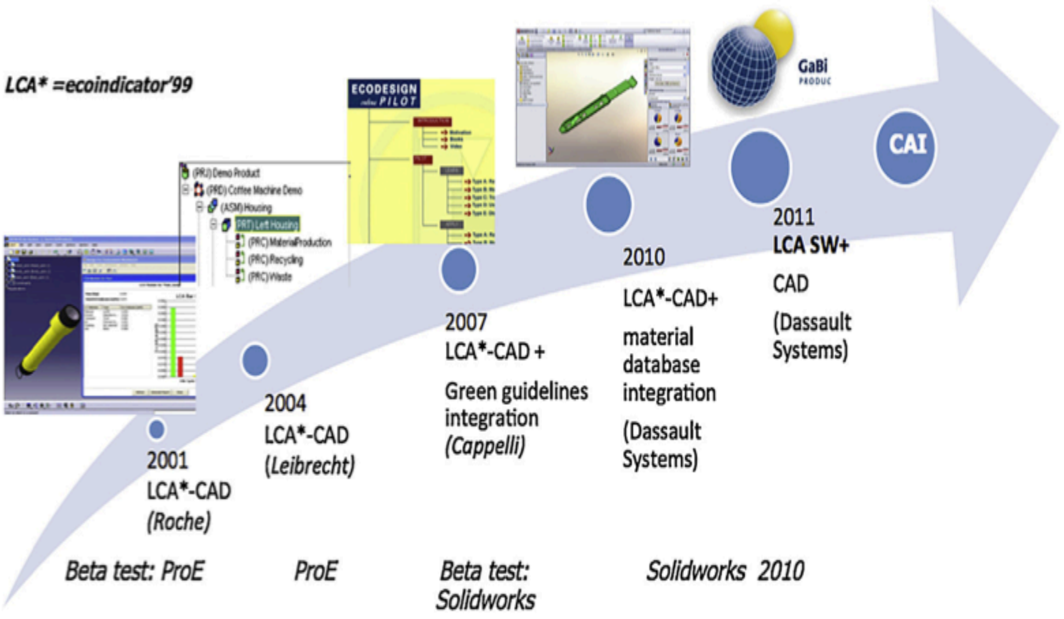


Figure 2-7: Evolution of CAD tools for eco-design (Russo et al., 2014).

2.4 Chapter Summary

The literature review chapter has contributed to get a first examination of the existing literature related to the sustainable implementation of product development processes. Eco-design has the potential to offer a different approach to develop products, taking into consideration environmental aspects at the same level as traditional features such as functionality, durability or costs. The literature review provided a confirmation of the lack of implementation of environmental requirements in product design process. Companies have now the commitment to optimize their product development processes through a wider scope able to evaluate the whole life cycle of a product.

Various tools and approaches for supporting the practice of eco-design are already available. New CAD software tools are emerging in order to integrate environmental analyses in the traditional product design process. The advantages of these CAD tools look very promising; however there are very few CAD tools offering an environmental analysis of products.

The main objective of the research of this thesis is to analyze the capability of these new CAD-integrated tools to perform an environmental analysis. To understand if the results from a CAD software tool correlate with the results from a traditional LCA is of especial interest as CAD software companies promote their own software as being superior because of the LCA features they offer.

CHAPTER 3. METHODOLOGY

This chapter includes the research framework, the data analysis, the sample set, and the units of measurement that will be used during the analyses. The purpose of this chapter is to identify possible tools to implement eco-design strategies in manufacturing to improve the sustainable product development processes. The main goal is to explain the research strategy and suggest a set of methods in which the several analyses will be performed. Detailed information of how the data will be gathered throughout the study and how the software outcomes will be interpreted to later write and discuss conclusions is also specified.

3.1 Research Framework

The concept of eco-design is growing in importance and becoming an area of focus for companies (Ostad-Ahmad-Ghorabi et al., 2009). Many eco-design tools available on the market are capable of identifying and quantifying the environmental impacts of products, but most of them fail because the design is not their main objective (Morbidoni et al., 2011). LCA tools are the most used technique for environmental assessment. However, LCA tools have been largely criticized for being time and expert dependent, and for the fact that they cannot be used in early stages of product development (Hatcher et al., 2001).

When the ecological footprint of a product needs to be evaluated in early design stages, the integration of LCA features in CAD software is a promising approach to perform environmental analyses (Ostad-Ahmad-Ghorabi et al., 2009). To help non-expert designers and companies design sustainable products, it is essential to implement digital tools that integrate sustainable techniques into CAD tools, enabling CAD users to more easily incorporate LCA information into their designs (Gaha et al., 2013). CAD programs able to integrate life cycle parameters of a product allow designers to be aware of the environmental impacts of their products within the product design and development process (“Solidworks,” 2014).

Russo et al. (2014) summarized the key aspects of CAD tools integrating eco-design features as follows:

- Intuitive design and user-friendly.
- Easy tracing of critical environmental hotspots.
- Easily implementable material. Additional information about any stage of a product’s life can be modified.
- Automatic recalculation of environmental impacts when volume or mass are changed.
- Structural and environmental parameters can be simultaneously analyzed with the same software.

In order to test these emerging CAD tools, this thesis will analyze their functionalities and compare them to the functionalities of a traditional and dedicated LCA. For this, a comparative study evaluating the results for the same scenario using a CAD software and a traditional LCA will be presented. The results will help LCA experts and designers understand the advantages and disadvantages of using these emerging CAD programs as tools to implement environmental procedures in early product development.

3.2 Data Analysis

A comparative case study is chosen for the basis of the research. A case study research "involves the study of an issue explored through one or more cases within a bounded system" (Creswell, 2007, p. 73). According to Creswell (2007) p.76 a case study is a "good approach when the inquirer seeks to provide an in-depth understanding of the cases or a comparison of several cases".

In order to compare a traditional LCA with an LCA performed by a non-dedicated LCA software (simplified LCA), three different evaluation methods are proposed. Figure 3.1 depicts the three methods. In each of the three different scenarios, a traditional LCA and a simplified LCA are performed. The four environmental impacts that will be compared in each scenario are: carbon footprint, acidification impacts, eutrophication impacts, and energy. Therefore and in order to make the comparison feasible, the evaluation of the environmental impacts are focused in a way that the environmental impacts available in the CAD tool are the same environmental impacts that will be analyzed in the traditional LCA software.

Figure 3-1: Methodology steps.

Figure 3.2 illustrates a more specific diagram of the proposed methodology including the different subsections of each of the previously mentioned sections. The chosen software to perform the traditional LCA is GaBi 6 with the education database 2013, and the chosen software to perform the simplified LCA is SolidWorks student edition 2014-2015 with the sustainability package. This software is available and for free for education purposes. The main reason for this selection is that SolidWorks is one of the few CAD software offering environmental analysis.

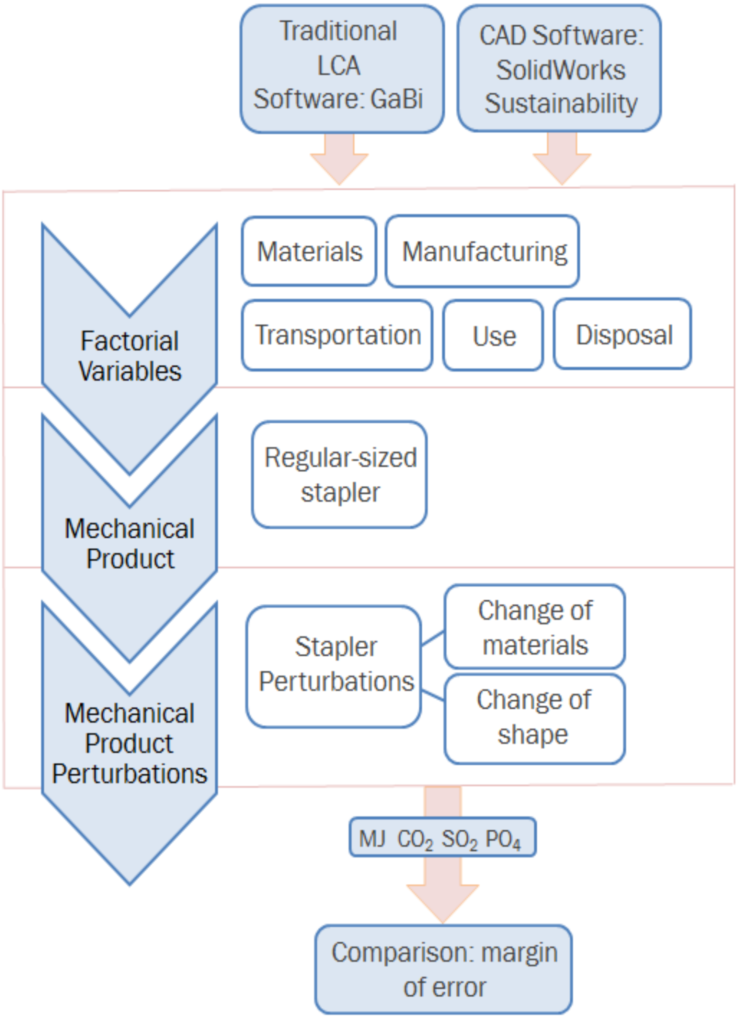


Figure 3.2: Methodology diagram.

In addition, PE International provides the databases for both GaBi and SolidWorks Sustainability.

The GaBi's database is integrated into the CAD software, collecting scientific data gathered by experts and empirical data collected over the years. SolidWorks Sustainability also offers an easy-to-use application with flexible input fields, including manufacturing processes, transportation modes, use phases, and different end of life scenarios. Parameters for different regions, such as energy usage and electricity consumption, are also provided.

Some of the key features and functions of SolidWorks Sustainability are provided as follows ("Solidworks," 2014):

- Intuitive LCA tool: it allows users to perform a quick and easy analysis.
- Environmental impact dashboard: it allows the users to instantly assess the product's impacts.
- Baseline measurement: the software first saves the environmental impacts of the original product to after compare them with the impacts of a new product.
- Similar material finder: a feature that allows designers to look for alternative materials.
- Integrated SolidWorks user interface and customizable reports.

SolidWorks Sustainability declares in their specifications that the environmental results have a estimated 20% margin of error. Next equation shows how the percentage of margin of error is calculated.

$$\left[\frac{(GaBi\ value - SolidWorks\ value)}{GaBi\ value}\right] \cdot 100$$

This 20% value is just an estimate that SolidWorks uses to inform users about the accuracy of the product. This margin of error means that the minimum or maximum expected difference between the true Gabi value and the SolidWorks Sustainability value will be -/+20%. Because 20% is the default percentage provided by SolidWorks Sustainability, it will be used in this thesis as the reference value for the products' comparison. However, if a more sensitive comparison was needed, the value could be changed to a different percentage. Nevertheless, all LCAs have some level of uncertainty but this high margin of error provided by SolidWorks demonstrates that the main weakness of the software might be its accuracy.

Since SolidWorks Sustainability is a software package available for purchase, it is particularly interesting to analyze if the estimated margin of error is maintained throughout the analyses. The function of this estimated margin of error will be to compare the output numerical value of the GaBi LCA and the output numerical value of the simplified SolidWorks Sustainability LCA, being kilograms of each category indicator (CO_2, SO_2, PO_4) and total energy (MJ), the final numerical values to be compared.

3.2.1 Factorial Variables

The first section of the methodology consists of evaluating SolidWorks Sustainability using simple inputs of the five different phases of the life of a product: raw material extraction, manufacturing process, transportation, use, and disposal. Two different input parameters for each stage will be tested. For example, for the material stage, two different types of materials will be evaluated. The selection of the input parameters will not follow any special order and the only requirement to be followed is that the input parameters in both GaBi and SolidWorks Sustainability must be available. The factorial variables analyses will help to understand if simple and isolated processes present different numerical results in SolidWorks Sustainability with respect to GaBi.

3.2.2 Mechanical Product

To understand if more complex products and processes provide different numerical outputs in a simplified LCA compared to a dedicated LCA, a whole product made with different materials and processes will be examined. In order to do so, a mechanical device is used for the comparison. The mechanical product that is used to perform the proposed methodology is a manual stapler, a mechanical device used to join two or more pages of paper. Table 3.1 displays the bill of materials for a manual regular-sized plastic stapler (Devanathan, Ramanujan, Bernstein, Zhao & Ramani, 2010).

Table 3.1: *Bill of materials for a regular-sized stapler (Devanathan et al., 2010).*

Part	**Material**	**Manufacturing process**	**Weight (g)**
Anvil	Low-carbon steel	Blanking and punching	13.9
Anvil actuator	Aluminum	Die casting	0.9
Base	Aluminum	Die casting	180.8
Base cover	Rubber	Molding	20.7
Clearing	ASTM Steel	Blanking and bending	9
Guide clamp	Low-carbon steel	Blanking and plating	31.7
Handle	HDPE	Injection molding	37.5
Magazine	Low-carbon steel	Blanking and plating	52.8
Pivot pin	Low alloy steel	Blanking and plating	2

Table 3.1 (continued)

Part	**Material**	**Manufacturing process**	**Weight (g)**
Punch/hammer	Low-carbon steel	Blanking and plating	3.2
Spring Rivet	Low-carbon steel	Forging	0.25
Staple advance	Low-carbon steel	Blanking and plating	2.5
Tension spring	Spring steel	Wire drawing	1.9

Since an LCA is ignorant of the actual shape of a product, the exact dimensions of the mechanical product are not required. Thus, in order to model the regular-sized stapler in SolidWorks Sustainability, the important requirement is to match the weight specifications displayed in table 3.1. In case the volume instead of the weight was provided, the density of each material would be used to identify the weight of every single component.

Once the environmental analyses of the stapler are completed, the main goal will be to compare the environmental impacts from GaBi and SolidWorks Sustainability respectively. After that, the margin of error will be calculated in order to quantify the difference in the impacts from the dedicated LCA and the impacts from the simplified LCA. This comparison will help to understand if the estimated margin of error is maintained when all the stages of the life of a product are taken into consideration at the same time. The parameters that do not match will be used to recognize the main similarities and inconsistencies between a dedicated LCA and a simplified LCA.

3.2.3 Mechanical Product Perturbations

To finally understand how SolidWorks Sustainability works and in order to better evaluate the accuracy of the software, some of the original features of the regular-sized stapler are exposed to different perturbations.

The first perturbation consists of changing the shape of the regular-sized stapler while having the constraint of maintaining the original weight of the components. This change of geometrical dimensions will help determine if volume alterations affect the performance of SolidWorks Sustainability.

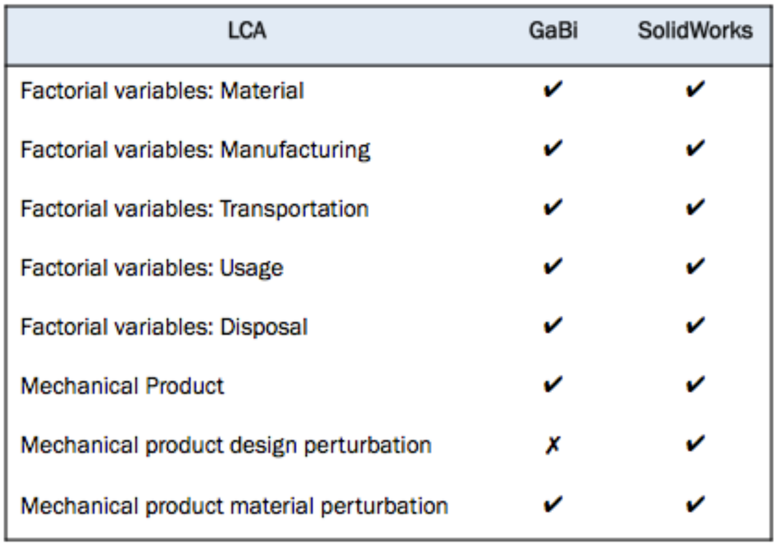
The design perturbation will not affect GaBi's original stapler LCA since the weight remains unaffected and in a dedicated LCA the geometric characteristics of a product do not affect the environmental impact (Nee, Song, & Ong, 2013). Therefore, GaBi's environmental impact results for the redesigned stapler will be reused for the subsequent comparison and only the SolidWorks analysis will have to be carried out.

The second perturbation consists of changing the original materials of certain components of the stapler. The parts that most affect the environment negatively will be the parts exposed to the material perturbations.

This change in materials will imply a weight alteration of the stapler and both GaBi and SolidWorks LCAs will have to be redesigned. This section will help to verify if different materials and different geometric characteristics can affect the performance of the CAD-integrated tool.

3.3 Sample Set

For this research two different analyses are used to analyze the three different sections of the methodology (factorial variables, mechanical product, and mechanical product perturbations). The first analysis consists of performing an LCA with an LCA dedicated software, in this case GaBi Education. The second analysis is developed through a CAD program integrating LCA features, in this case SolidWorks Sustainability. Figure 3.3 summarizes the total number of LCAs that will be performed in this thesis.



LCA	GaBi	SolidWorks
Factorial variables: Material	✔	✔
Factorial variables: Manufacturing	✔	✔
Factorial variables: Transportation	✔	✔
Factorial variables: Usage	✔	✔
Factorial variables: Disposal	✔	✔
Mechanical Product	✔	✔
Mechanical product design perturbation	✗	✔
Mechanical product material perturbation	✔	✔

Figure 3.3: Summary of total number of LCAs.

3.4 Units of Measurement

The environmental impact category indicators are “the quantifiable representation of an impact category” (ISO, 2006, p.4). The default category indicators provided by SolidWorks Sustainability will be used as the reference indicators to compare the two different LCA methods. The impact categories and their respective category indicators that will be assessed are listed as follows (Guinée et al., 2002):

- Carbon footprint [CO_2]: a measure of carbon dioxide and equivalents that are released into the atmosphere.
- Total energy consumed [MJ]: it accounts the non-renewable energy consumed over the life cycle of a product.
- Acidification [SO_2]: air impacts caused by the release of certain polluting gases into the atmosphere. The acidification emissions are the main cause of acid rain.
- Eutrophication [PO_4]: when nitrates and phosphates contaminate the water ecosystems, causing the contamination of fresh and marine waters.

3.5 Chapter Summary

The methodology chapter examined the research that will be conducted and revealed the proposed methodology for the research study. In addition, this chapter also described how the data will be collected, and presented three methods for comparing the software. The units of measurement to perform the comparison have also been specified. The suggested research will study through three comparative case studies if SolidWorks Sustainability as a CAD tool integrating new LCA methods, is an acceptable and feasible software to perform valid life cycle analyses of products. Finally, the results of all the analyses will help to decide if CAD tools allowing sustainable product development have potential and become relevant in the future of engineering.

CHAPTER 4. RESULTS

This chapter presents the outcomes from the three different sections previously presented in the methodology chapter. First of all, GaBi and SolidWorks Sustainability are tested using very simple inputs. The use of simple inputs will help to understand the fundamentals of how both software present the results. Secondly, in order to test how the SolidWorks Sustainability works as a whole, a detailed product is analyzed; in this case a manual regular-sized stapler. Finally, the regular-sized stapler is exposed to numerous perturbations, including a change of the shape of some of its components and a change of some of its original materials to some new materials.

There are many different available methodologies to analyze the environmental impacts of products. These methodologies measure the environmental effects of products and differ from one another in the impact categories that they analyze and encompass. SolidWorks Sustainability offers two different multiple-indicator methodologies: the CML 2001 and the TRACI methodologies. The TRACI methodology differs from the CML 2001 methodology in that the data comes from North American sources, while the CML 2001 is developed by the University of Leiden and primarily uses European data (SolidWorks, 2014). The chosen methodology for all the analyses is the CML 2001. This methodology is also considered more comprehensive and complete than the TRACI methodology (SolidWorks, 2014).

4.1 Factorial Variables

This section consists of evaluating the software using very simple inputs. The software measures the environmental impacts based on five different parameters: material, manufacturing process, use region, transportation, and disposal. The objective of this section is to separately analyze these five stages in order to understand if major differences in the analytical results of each stage exist. Two different random input parameters for each stage will be evaluated. Although the environmental impacts of a product are associated to the whole life cycle of a product, the environmental impacts of each section can be individually identified. This is possible because of the way GaBi and SolidWorks calculate their environmental values. While Gabi displays the values of the different impact sources in a bar graph, SolidWorks displays separately the impacts related to each of the five stages of an LCA. However, the specific contributing factors of each environmental impact cannot be effectively differentiated in any of the software.

4.1.1 Material

The material selection is one of the key stages of a product's life in an LCA.

GaBi Education has only one integrated database and offers fully functional software with access to a limited number of materials. When other databases are required, those have to be purchased separately. SolidWorks Sustainability offers a fixed number of materials, making the number of available materials in GaBi bigger than in SolidWorks Sustainability. SolidWorks Sustainability also differs from GaBi because it offers a setting to find a similar material based on the mechanical properties of the original material. The environmental impacts of the new material are then compared to the original impacts of the first material. After the comparison, a future decision of the preferred material can be made. The proposed material analyses are evaluated using one kilogram of a randomly picked material as the testing product. The only restriction when choosing the material is that to find the material in both GaBi and SolidWorks databases. Table 4.1 and Table 4.2 summarize the numerical values of the environmental impacts for one kilogram of Polyethylene terephthalate (PET) and one kilogram of glass respectively. The PET and glass results do not show any similarities and the results are close to the stated +/- 20% margin of error. SolidWorks does not provide the sensitivity of the margin of error; therefore the results must be treated as estimates.

Table 4.1: *Environmental impacts of one kilogram of PET.*

1 Kg PET	**GaBi**	**SolidWorks**	**Error**
Kg CO_2e	2.97	2.90	-2.36%
Kg SO_2e	0.00517	0.00520	+0.58%
Kg PO_4e	0.000494	0.000490	-0.81%
MJ	64.3	80	+24.42%

Table 4.2: *Environmental impacts of one kilogram of glass.*

1 Kg Glass	**GaBi**	**SolidWorks**	**Error**
Kg CO_2e	0.97	1.30	+23.38%
Kg SO_2e	0.0054	0.0049	-10.20%
Kg PO_4e	0.00070	0.00088	+20.45%
MJ	15.79	14	-12.79%

4.1.2 Manufacturing

The manufacturing process is the second stage in a cradle-to-grave analysis. Firstly, the manufacturing region must be selected. SolidWorks Sustainability provides seven regions to pick from: Europe, North America, South America, Japan, Australia, Asia, and India. Once the desired region is selected, the user has to estimate the product's lifespan, with a minimum input of 0.1 hour and a maximum of 1000 years. Subsequently, SolidWorks Sustainability presents different manufacturing processes specific to the previously selected material. The fuel consumption related to the manufacturing process can be also indicated (electricity or natural gas). Finally, the percentage of scrap rate and the type of paint can be chosen.

A main difference between GaBi and SolidWorks Sustainability is that no other fuel different than electricity or natural gas can be selected in SolidWorks. However, GaBi can include other materials in the manufacturing process. For example, Figure 4.1 shows how water is also taken into account in the injection molding process and how the materials and fuels are specific to 27 countries of the European Union (EU-27).

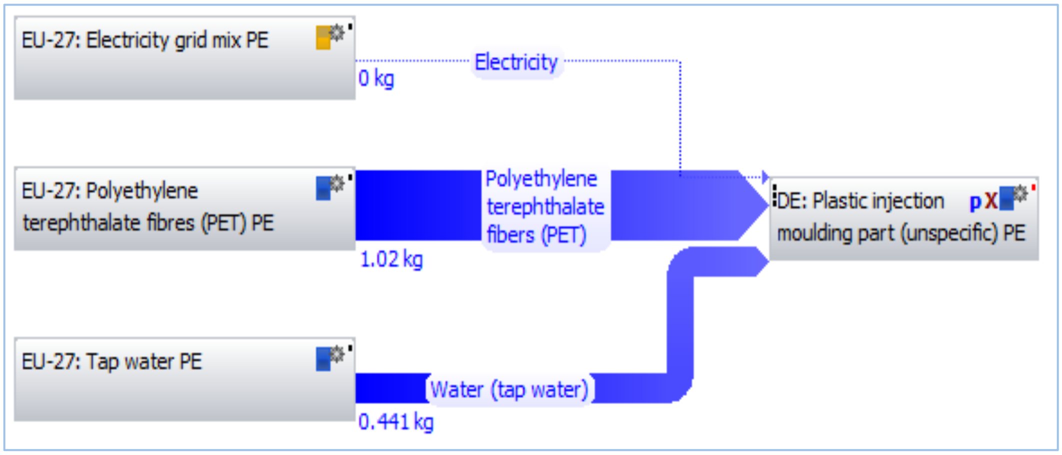


Figure 4.1: GaBi's diagram screenshot for one kilo of injected PET.

Another significant difference between the two programs is how the results are presented. GaBi displays separate graphs for every different environmental impact. In addition, each environmental impact has different columns with the numerical results related to the specific materials and processes used in the analysis. Figure 4.2 shows an example of how GaBi displays the environmental impacts reports.

On the other hand, SolidWorks Sustainability displays the total environmental impacts without providing any specific information about the used materials or resources in the analysis. SolidWorks Sustainability displays the impacts in a pie chart identifying the most critical stages of the life of a product (see Figure 4.3).

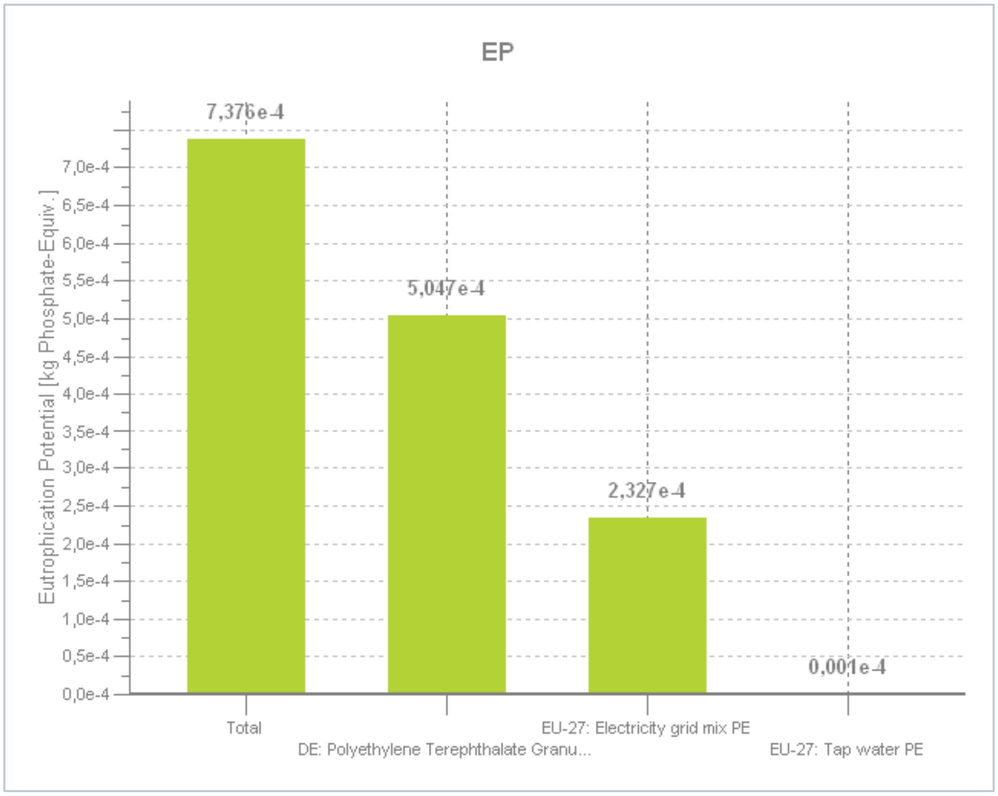


Figure 4.2: GaBi's dashboard screenshot (eutrophication impacts).

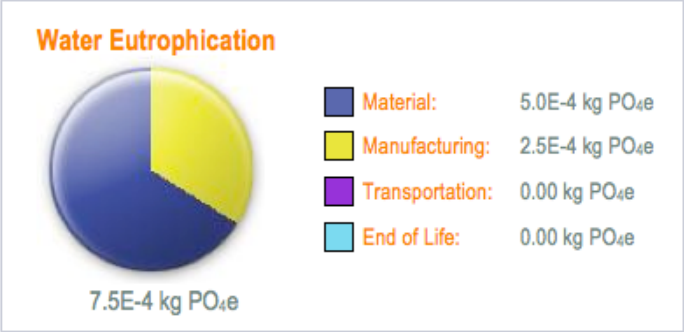


Figure 4.3: SolidWorks' dashboard screenshot (eutrophication impacts).

The next two tables, Table 4.3 and Table 4.4 summarize the numerical values provided by GaBi and SolidWorks Sustainability for the manufacturing processes of injection molding and die-casting respectively.

The +/-20% estimated margin of error is no longer maintained in the manufacturing stage. A reason for this margin increase could be due to the fact that SolidWorks takes into account parameters from the material stage and since the results from that stage are not identical, SolidWorks Sustainability creates an even bigger gap in the results. Therefore, when comparing the environmental impacts from SolidWorks with the environmental impacts from GaBi, the margin of error tends to increase.

Table 4.3: *Environmental impacts of injection molding.*

Injection molding	**GaBi**	**SolidWorks**	**Error**
Kg CO_2e	0.88	1.0	+13.64%
Kg SO_2e	0.0041	0.0070	+70.73%
Kg PO_4e	0.000233	0.00025	+7.29%
MJ	53.3	20	-62.47%

Table 4.4*: Environmental impacts of die-casting.*

Die Casting	**GaBi**	**SolidWorks**	**Error**
Kg CO_2e	1.51	1.60	+5.96%
Kg SO_2e	0.00921	0.011	+19.44%
Kg PO_4e	0.00076	0.00038	-50%
MJ	37.04	30	-19.01%

4.1.3 Transportation

The transportation section allows the user to determine the transportation mode and distance from the manufacturing site to the deployment destination. There are four transportation methods available in SolidWorks Sustainability: train, truck, boat, and plane. GaBi offers more features than SolidWorks, enabling the user not just to select the payload of the vehicle, but also the fuel type and its country of origin. In addition, GaBi allows the user to create as many transportation scenarios as desired. For example, a GaBi LCA can include the transportation from the materials extraction site to the manufacturing location and the transportation from the manufacturing site to the final user destination. In SolidWorks Sustainability the fuel and payload of the vehicles are not indicated or customizable, making the comparison fairly inaccurate. For this, when calculating the environmental impacts related to the transportation stage, GaBi takes into account the total liters of fuel to cover the designated distance, while the detailed data that SolidWorks Sustainability uses to calculate the environmental impacts remains unknown to the user.

The environmental impacts related to land, sea and air transportation modes vary dramatically. The metrics that the LCA methodologies use to analyze the equivalent kilograms of each impact indicator are the weight of cargo by the total distance traveled. Two different transportation scenarios to evaluate the related environmental impacts are presented. Both scenarios consist of transporting a single product that weights one kilogram.

The first scenario consists of a distance of 2000 kilometers travelled by train and the second scenario consists of a truck traveling a 1000 km distance. Table 4.5 and Table 4.6 show the environmental impacts related to that transportation scenarios. All the numerical results have a very small magnitude, and therefore, any little change in the magnitude gives substantial error percentages.

Since GaBi displays the specific source of the environmental impacts in different columns as showed in Figure 4.2, the fuel for the truck transportation scenario can be excluded. Excluding the fuel from the analytical results will help investigate if the fuel type affects the software comparison.

In Table 4.6, the first GaBi column (GaBi $_1$) includes the fuel type in the GaBi analysis, while the second GaBi column (GaBi $_2$) does not take fuel into consideration. The results demonstrate that the new margin of error (error$_2$) is smaller when fuel is not taken into account. Therefore, if SolidWorks wants to improve the accuracy of their environmental analyses, the fuel option should be added as a feature in their transportation section.

Table 4.5: *Environmental impacts of a train carrying 1kg during 2000 km.*

2000 km Train	**GaBi**	**SolidWorks**	**Error**
Kg CO_2e	0.05	0.0074	-85.2%
Kg SO_2e	0	0.000066	≈ 0%
Kg PO_4e	0.000033	0.000015	-54.54%
MJ	1.56	0.098	-93.72%

Table 4.6: *Environmental impacts of a truck carrying 1kg during 1000 km.*

1000 km Truck	**GaBi $_1$**	**GaBi $_2$**	**SolidWorks**	**Error $_1$**	**Error $_2$**
Kg CO_2e	0.06	0.05	0.047	-21.67%	-6%
Kg SO_2e	0	0	0.00022	≈ 0%	≈ 0%
Kg PO_4e	0.000092	0.000085	0.00005	-45.65%	-41.17%
MJ	0.87	0.73	0.696	-20%	-4.66%

4.1.4 Use

The use stage is the stage where the consumer has the entire control of the product and it can be one of the crucial stages of an LCA. In a dedicated LCA, the materials or fuels needed to run or use the product over its lifespan are included. Some examples of materials that are typically included in the use stage are: electricity, water, oil, spare parts, or cleaning products.

However, in SolidWorks Sustainability only the use region is used as an input variable when modeling an isolated part. The offered regions are the same regions previously available in the manufacturing process stage: Europe, North America, South America, Japan, Australia, Asia, and India.

Changing the use region while maintaining the transportation distance as a fixed number produces changes exclusively to the numerical results of the transportation impacts. These changes might be due to some unknown software configuration in the transportation vehicles or the fuel properties depending on the usage region.

4.1.5 End of life

The end of life or disposal stage is the final stage of a product's life. This final stage covers the disposal impacts of a product. SolidWorks Sustainability offers three end of life scenarios: recycling, incineration, and landfill. The percentage of each of the three options can be chosen in order to fully describe the disposal of the product being analyzed, thus the total sum of the three disposal scenarios always equals 100%. GaBi's landfill section is more specific than SolidWorks. It offers many different sub-options, such as type of incineration plant or different waste disposal depending on the waste type: municipal waste, domestic waste, hazardous waste, etc.

Table 4.7 shows the numerical values associated with the incineration of one kilogram of PET and Table 4.8 displays the environmental impacts of disposing one kilogram of copper to landfill. The copper landfill results (Table 4.8) respect the estimated +/-20% margin of error, but the results related to the PET incineration are quite irregular. While GaBi presents a negative value for the air and water impacts from the incineration process (Table 4.7), SolidWorks gives a positive numerical result, contributing to a margin of error bigger than 25%.

Table 4.7: *Environmental impacts of incineration.*

1 kg PET Incineration	**GaBi**	**SolidWorks**	**Error**
Kg CO_2e	1.17	1.30	-11.11%
Kg SO_2e	-0.008	0.0011	+86.25%
Kg PO_4e	-0.000297	0.00022	+25.93%
MJ	4.94	1.0	-79.76%

Table 4.8: *Environmental impacts of landfill.*

1 kg Copper Landfill	**GaBi**	**SolidWorks**	**Error**
Kg CO_2e	0.01	0.012	+20%
Kg SO_2e	0	0.000074	≈ 0%
Kg PO_4e	0.000008	0.0000096	+20%
MJ	0.180	0.160	-11.11%

A negative value as an environmental impacts means that the environmental gains are higher than the environmental impacts, however these negative values belong exclusively to the incineration stage, meaning that the total environmental impacts could still be positive. The reason for getting negative results can be explained because GaBi's incineration model uses a waste-to-energy approach, and the heat and steam leaving the incineration plant is used for power generation. The waste-to-energy approach is also reflected in the value of total energy of the incineration scenario, where GaBi gives a value of 4.94 MJ and SolidWorks Sustainability gives 1.0 MJ, a value 80% smaller than the original GaBi value.

4.2 Mechanical Product

The previous section was used to evaluate how Gabi and SolidWorks Sustainability analyze separately the environmental impacts of simple and isolated components. This next section is used to analyze how GaBi and SolidWorks Sustainability perform when evaluating the environmental impacts of a complete assembly.

An LCA usually demands specified and complete product information, therefore a real product, in this case a manual regular-sized stapler, is used in the analyses. The proposed life cycle and system boundaries of the regular-sized stapler are displayed in Figure 4.4. The used materials for the components of the stapler come from the bill of materials and are divided into plastic, steel, and aluminum. The total weight of assembly is 357.15 grams. The transportation scenario is set to a distance of 3000 kilometers travelled by truck. Only the usage region can be chosen in the usage stage in SolidWorks Sustainability, therefore, in order to make the comparison more realistic, no maintenance or replacements will be needed throughout the stapler's life. Finally, the chosen disposal scenario for the stapler will be incineration.

Subsection 4.2.1 and Subsection 4.2.2 describe in detail the two types of analyses that will be performed, a GaBi analysis and a SolidWorks Sustainability analysis respectively.

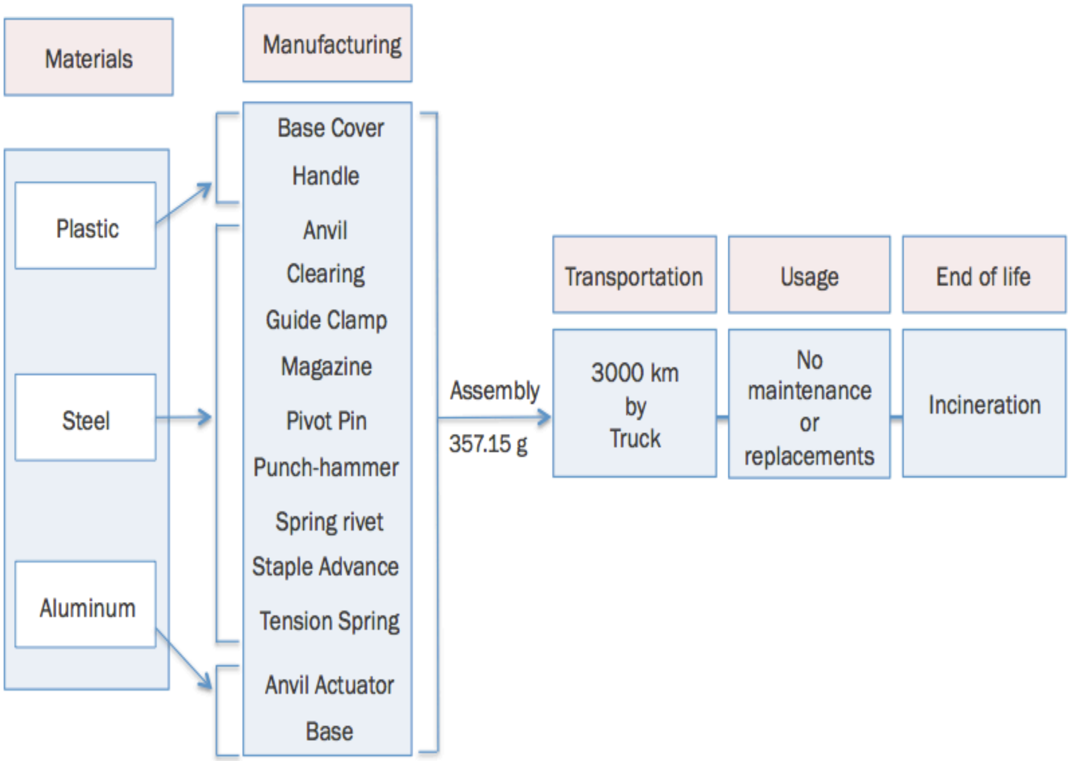


Figure 4.4: Proposed regular-sized stapler's lifecycle.

4.2.1 Mechanical Product: GaBi analysis

In order to evaluate the regular-sized stapler with GaBi, the study is divided in three different sections depending on the materials of the stapler: plastic components (58.20 grams), aluminum components (181.70 grams), and steel components (117.25 grams). Appendix A shows the three different diagrams used to gather all the stapler's components and to analyze the environmental impacts of the stapler in GaBi.

Figure 4-4, Figure 4-5, Figure 4-6, and Figure 4-7 show the regular-sized stapler's carbon footprint, acidification potential, eutrophication potential, and total energy analyzed with GaBi Education. These GaBi results will be later compared to the SolidWorks analytical values.

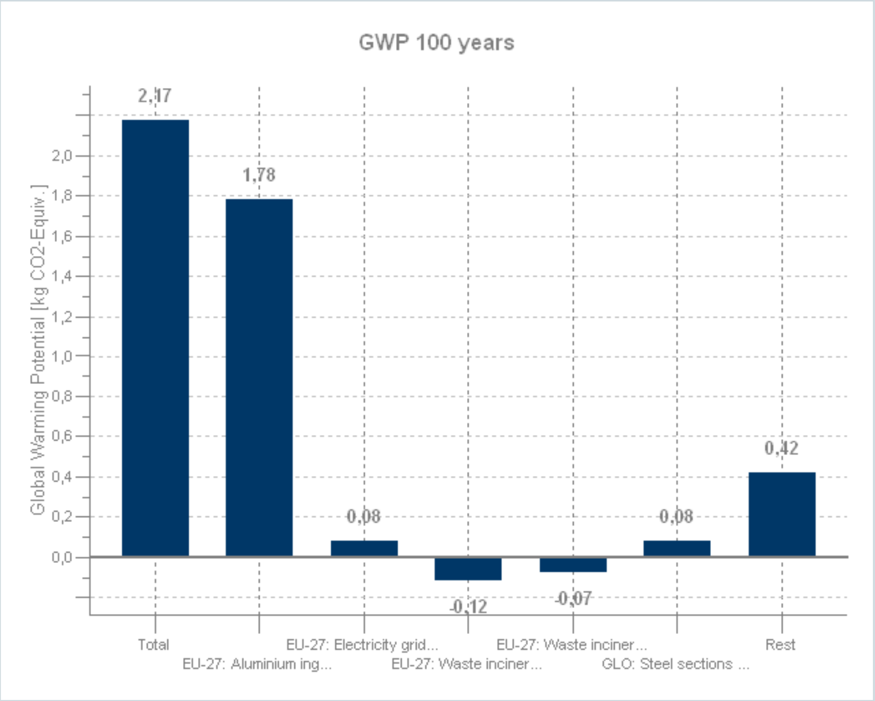


Figure 4.5: Stapler's Carbon impacts (GaBi).

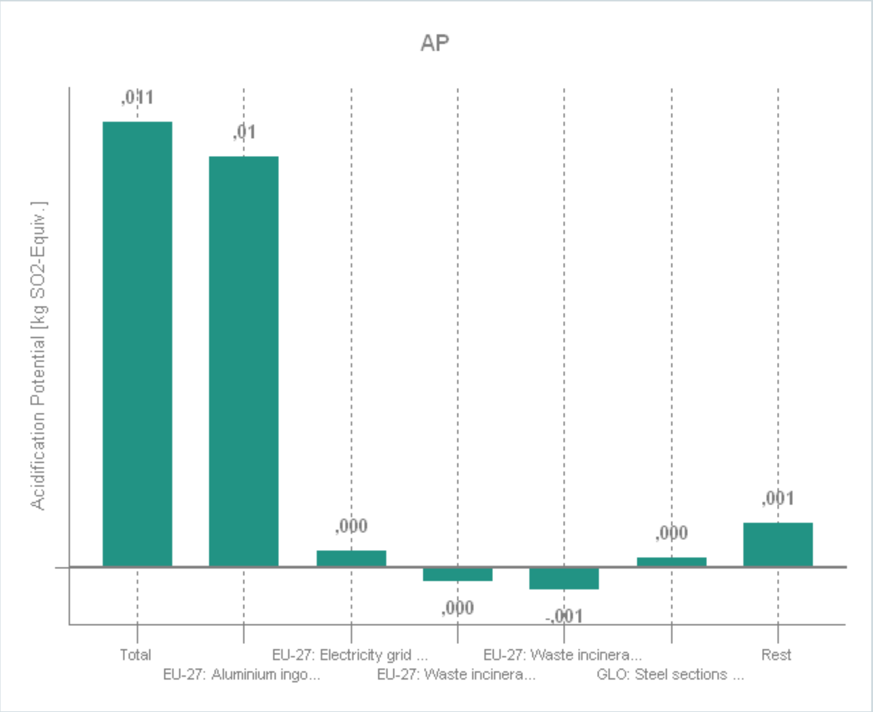


Figure 4.6: Stapler's air acidification impacts (GaBi).

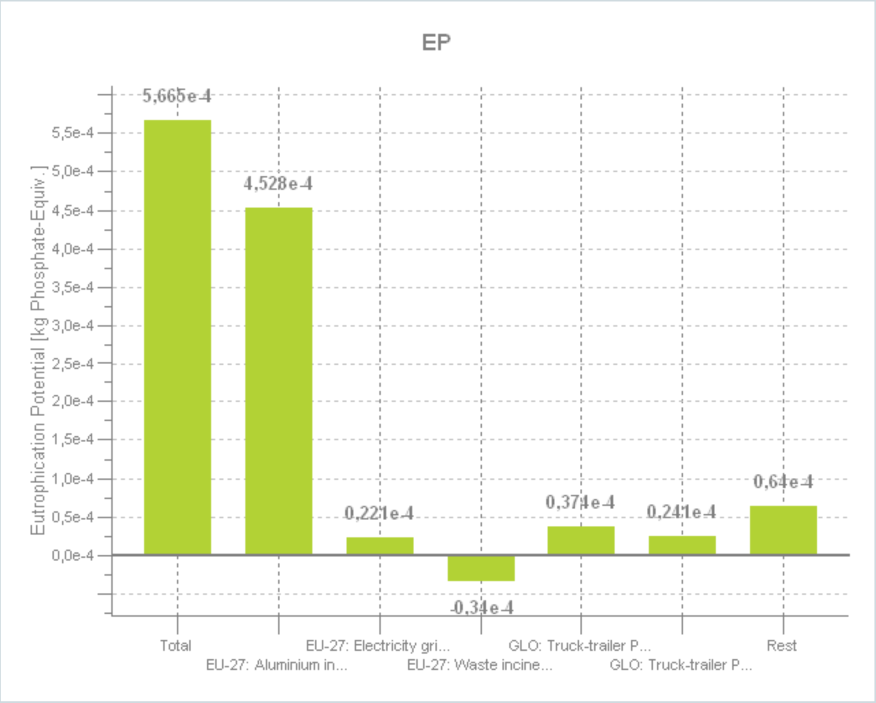


Figure 4.7: Stapler's eutrophication impacts (GaBi).

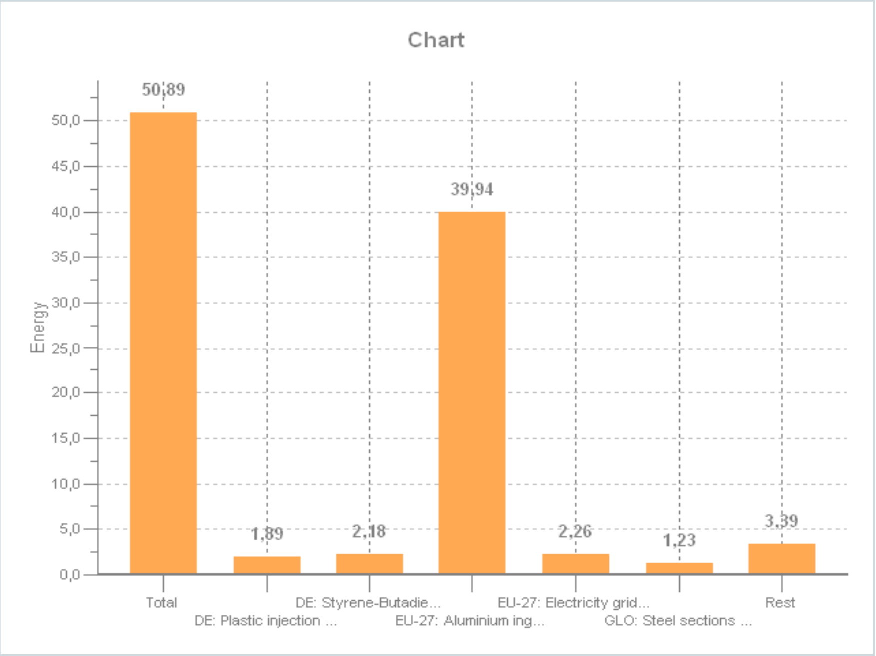


Figure 4.8: Stapler's total energy (GaBi).

4.2.2 Mechanical Product: SolidWorks analysis

One of the best ways to test an integrated LCA tool in a CAD software, is to use a real object to simulate the procedure. Table 3.1 previously showed the bill of materials of a disassembled manual regular-sized stapler. Unfortunately, the measures of each stapler's component are not specified. However, the main motivation of this section is to analyze the environmental impacts of the regular-sized stapler using GaBi and SolidWorks Sustainability. Therefore, in order to model and evaluate the stapler with SolidWorks Sustainability, the only prevailing limitation is to match the weight specifications of each part of the stapler with all the weights previously presented in Table 3.1. Excluding the actual dimensions of the stapler should not alter the analyses since the LCA methodology is driven by the weight of the product. Any change in volume will not affect the environmental impacts as long as the weight of the components remains unaffected. This fact will be later verified in section 4.3.

Figure 4.9 and Appendix B provide a 3D rendering and an exploded view respectively of the proposed design for the stapler. There are no major differences in SolidWorks Sustainability when it comes to analyzing an isolated part or a whole assembly. Editing or adding materials to an assembly is quite simple and the right values can be adjusted easily if a component has not been previously defined.

The main difference between analyzing an isolated part or a whole product is that in the product, the energy requirements for the assembling process and the energy needs of a product over its lifespan can be included, although the available fuel options are very limited (see Figure 4.10).

An extra feature of analyzing a complete product is that the transportation mode can be edited twice, during the part modeling and in the assembly itself.

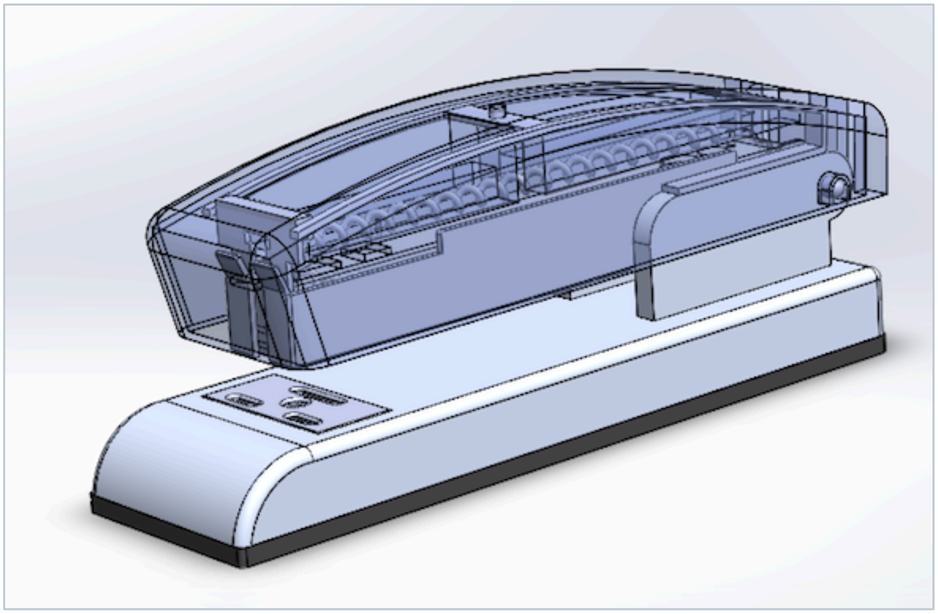
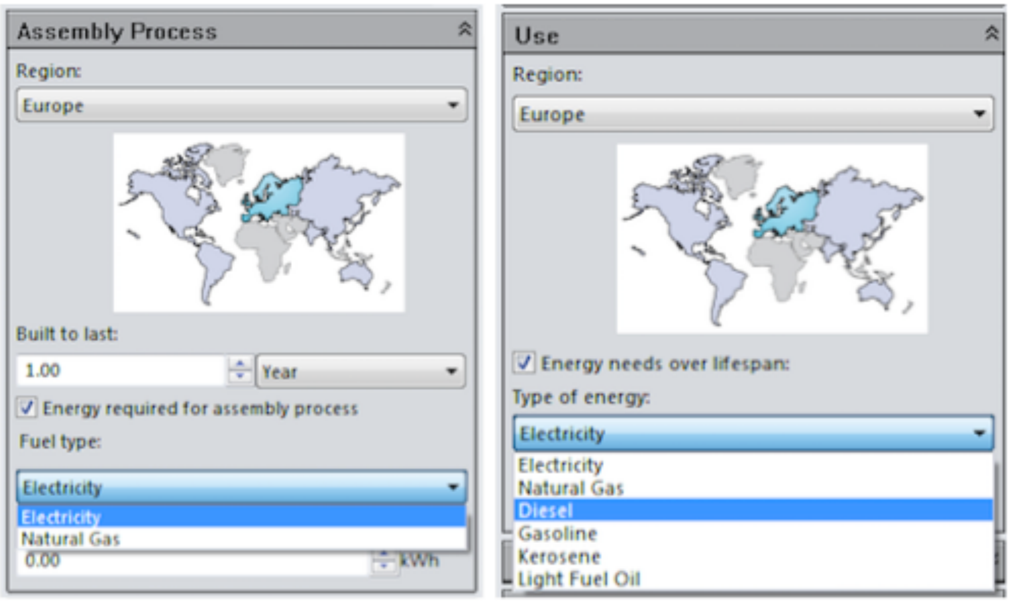


Figure 4.9: 3D SolidWorks rendering of the regular-sized stapler.



Assembly Process

Region: Europe

Built to last: 1.00 Year

☑ Energy required for assembly process

Fuel type: Electricity

0.00 kWh

Use

Region: Europe

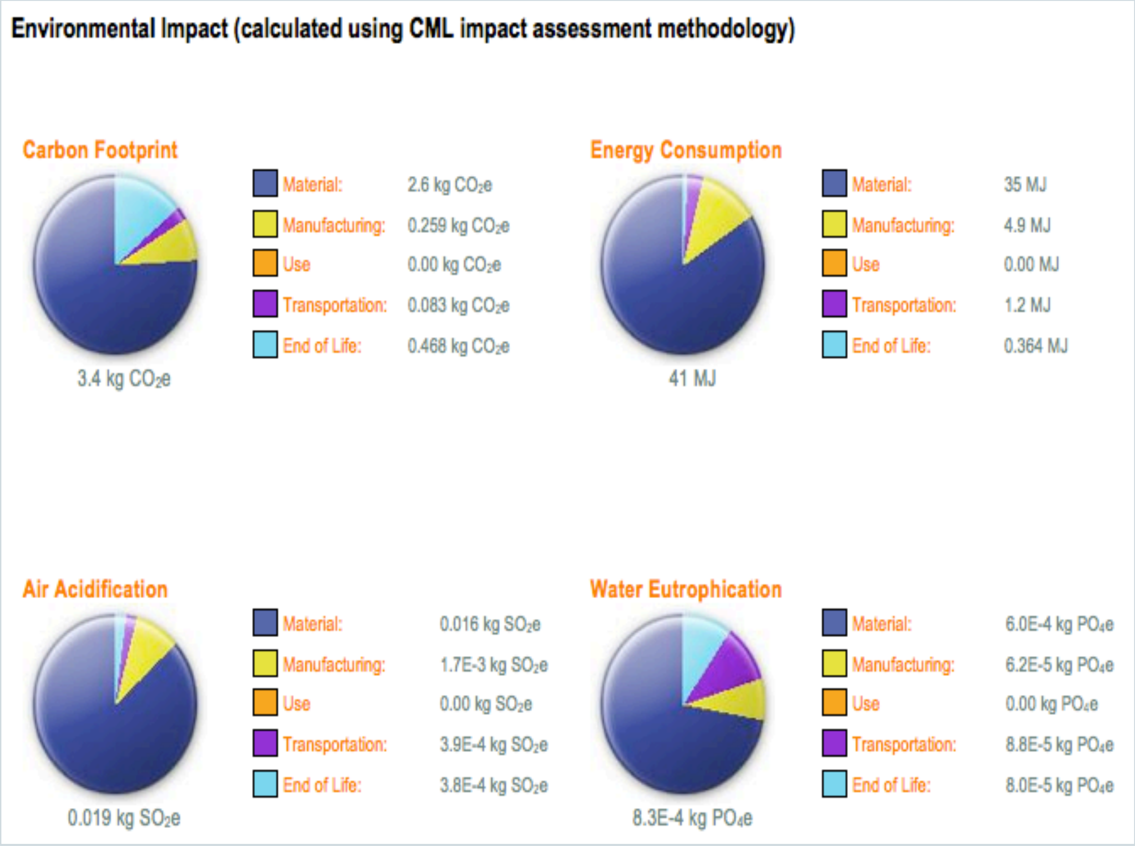
☑ Energy needs over lifespan:

Type of energy: Electricity

*Figure 4.10:*Assembly process in SolidWorks Sustainability.

In order to evaluate the stapler with SolidWorks, only the transportation distance of the assembly is set to the fixed value of 3000 km. Once all the information about the assembly is introduced, the results can immediately be seen on screen. Any change in the original input data leads to a recalculation of the environmental impacts and at the same time, SolidWorks offers an instant comparison of the product with the before and after impacts. The environmental impacts are depicted with colors (green or red) to indicate if a new material is more or less environmentally friendly than the original material.

Finally, SolidWorks creates a Word document report with the entire sustainability profile of the reviewed product. Figure 4.11 displays the sustainability profile of the regular-sized stapler.



Environmental Impact (calculated using CML impact assessment methodology)

Carbon Footprint

Material: 2.6 kg CO_2e
Manufacturing: 0.259 kg CO_2e
Use: 0.00 kg CO_2e
Transportation: 0.083 kg CO_2e
End of Life: 0.468 kg CO_2e

3.4 kg CO_2e

Energy Consumption

Material: 35 MJ
Manufacturing: 4.9 MJ
Use: 0.00 MJ
Transportation: 1.2 MJ
End of Life: 0.364 MJ

41 MJ

Air Acidification

Material: 0.016 kg SO_2e
Manufacturing: 1.7E-3 kg SO_2e
Use: 0.00 kg SO_2e
Transportation: 3.9E-4 kg SO_2e
End of Life: 3.8E-4 kg SO_2e

0.019 kg SO_2e

Water Eutrophication

Material: 6.0E-4 kg PO_4e
Manufacturing: 6.2E-5 kg PO_4e
Use: 0.00 kg PO_4e
Transportation: 8.8E-5 kg PO_4e
End of Life: 8.0E-5 kg PO_4e

8.3E-4 kg PO_4e

Figure 4.11: SolidWorks environmental impacts for the regular-sized stapler.

In addition, the Word report also informs about what assembly components have the greatest impact on each of the environmental impacts of the stapler. Figure 4.12 shows the ten components of the stapler that contribute the most to the total environmental impacts of the stapler.

The hot-spot analysis (Figure 4.12) is a very useful feature as it helps the designer to rapidly acknowledge the components of the assembly that negatively affect the environment the most and it helps to find substitute materials or processes for those critical components. Once the information about the components is listed, the designer is able to accordingly look for alternatives for lowering the products' environmental impacts .

Component	Carbon	Water	Air	Energy
Base	2.7	6.0E-4	0.017	31
Handle	0.162	3.5E-5	4.7E-4	3.6
Magazine	0.173	4.2E-5	3.7E-4	1.5
Base cover	0.100	2.2E-5	1.6E-4	2.0
Guide clamp	0.104	2.5E-5	2.2E-4	0.886
Clearing	0.033	2.5E-5	7.3E-5	0.283
Anvil	0.047	1.2E-5	1.2E-4	0.423
Anvil actuator	0.013	3.0E-6	8.4E-5	0.156
Spring	0.011	5.1E-6	3.7E-5	0.129
Pin	7.6E-3	4.3E-6	2.0E-5	0.069

Figure 4.12: Hot-Spot analysis of the stapler's components.

The hot-spot analysis recognized the base as the component of the manual regular-sized stapler that clearly contributes the most to the total environmental impacts. The base of the stapler weights 180.8 grams and it is the largest component in the assembly, however the weight is not the only deciding factor in the hot-spot analysis. For example, the environmental numerical results of the low-carbon steel magazine (52.8 grams) are smaller than the environmental numerical results of the HDPE handle (37.5 grams).

Now that both the GaBi and SolidWorks analyses for the regular-sized stapler are performed, the results can be compared. Table 4.9 summarizes the comparison of results as well as the margin of error.

As previously happened in section 4.1, the results present very small numerical values for the environmental impacts. The compared results share the same order of magnitude, but small variations produce big differences. Therefore, only the energy impact satisfies the estimated accuracy ratio of SolidWorks Sustainability of being useful to within +/-20%.

Table 4.9: *Regular-sized stapler comparison (GaBi vs SolidWorks)*

Stapler	**GaBi**	**SolidWorks**	**Error**
Kg CO_2e	2.17	3.4	+56.68%
Kg SO_2e	0.011	0.019	+72.73%
Kg PO_4e	0.0005665	0.00083	+46.51%
MJ	50.89	41	-19.43%

4.3 Mechanical Product Perturbations

This final section is used to understand the precision of SolidWorks Sustainability compared to GaBi. In order to do so, the regular-sized stapler is exposed to different perturbations.

First of all, the design of the stapler is changed. This perturbation helps to definitively understand if SolidWorks Sustainability performs the LCA exclusively using the weight of the product or if it takes other features such as shape or dimensions into account. The second perturbation consists of changing the original materials into other materials. This material perturbation helps to analyze how GaBi and SolidWorks Sustainability independently react to these changes.

In order to compare and analyze the two different programs, the percentage of change from the original stapler to the new stapler is compared. This evaluation helps to identify if changes in material generate similar or different alterations in the environmental impacts of the product.

4.3.1 Design Perturbations

The first perturbation consists of changing the shape of some components of the stapler while the weight of the original components remains constant. The chosen components are the four parts of the regular-sized stapler previously identified in Figure 4.12 as the parts that affect the most to the environment: base, base cover, handle, and magazine. Figure 4.13 and Table 4.10 show respectively the new rendering as well as the numerical results of the redesigned stapler.

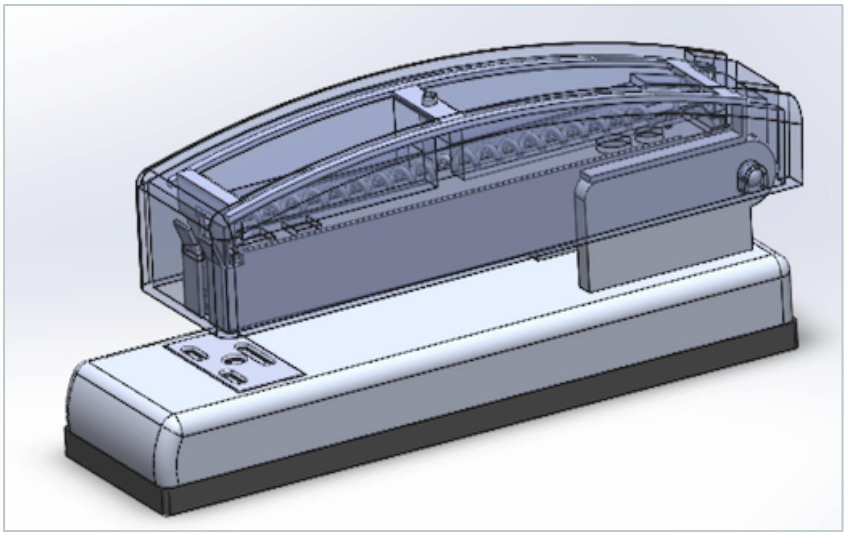


Figure 4.13: Rendering of the redesigned stapler.

Table 4.10: *SolidWorks original and redesigned staplers' comparison.*

	Carbon Footprint	**Air Impacts**	**Water Impacts**	**Energy**
Stapler design 1	3.4	0.019	0.00083	41
Stapler design 2	3.4	0.019	0.00083	41

The analytical results occurred to be exactly the same as with the first design and consequently, it is possible to validate that different shapes in the design do not affect the performance of SolidWorks Sustainability.

4.3.2 Material Perturbation

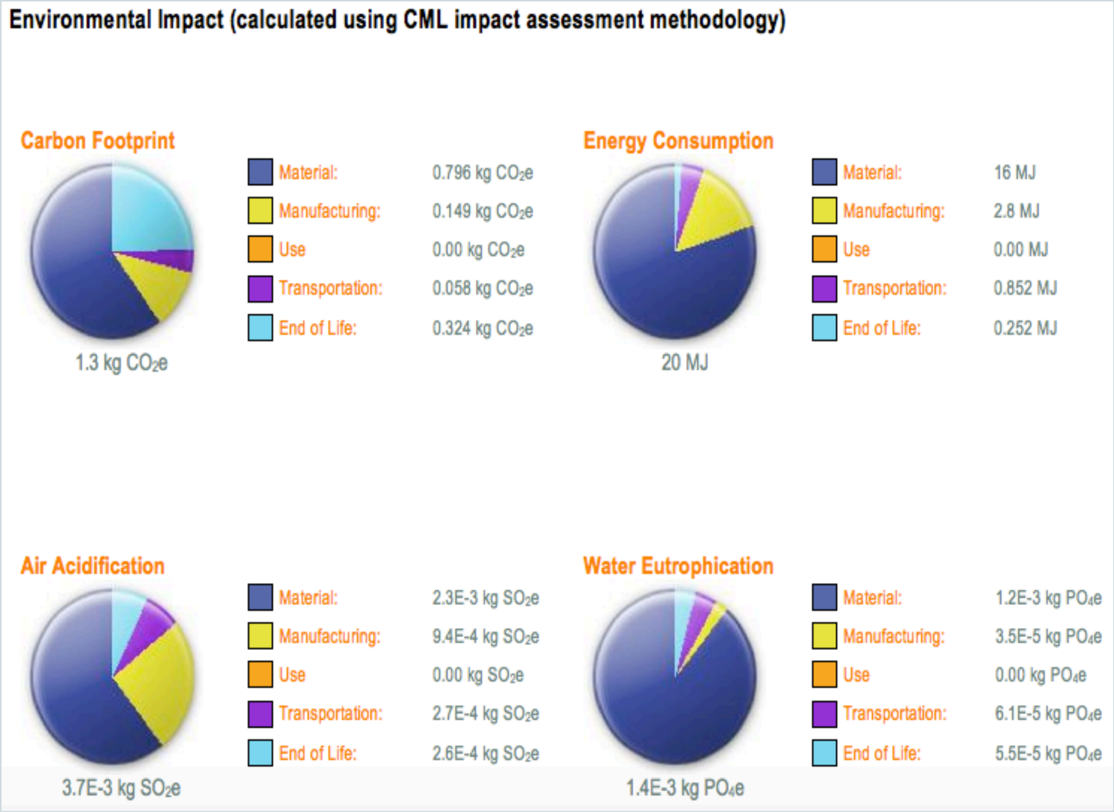
The second perturbation consists of changing some of the original materials of the manual regular-sized stapler to some new materials. This perturbation will help analyze and understand if the margin of error when comparing SolidWorks Sustainability to GaBi simultaneously increases or decreases.

Only the four components that affect the environmental impacts most are changed. According to the hot-spot analysis from section 4.4.2, the four parts are the base, base cover, handle, and magazine. The new materials are chosen following no particular criteria with regard to product performance. The only prerequisite that has been followed is to use materials that are frequently used in this type of products. The new materials may differ with the original materials in terms of material quality, long-term performance, or product durability. These assumptions may limit the analyses in terms of credibility, but they do not affect the outcome of the environmental analysis. In a real life scenario the materials should be chosen accordingly to the purpose of the product.

The density of the new set of materials is different, thus, the total weight of the stapler will change from its original 357.15 grams to 247.39 grams. This weight reduction is expected to bring a decrease in the numerical results of the environmental impacts of both LCA programs. Table 4.11 shows the configuration for the manual stapler with the new weights of the four selected components and Figure 4.14 illustrates the SolidWorks Sustainability environmental impacts related to that stapler with new materials.

Table 4.11*: Stapler's new bill of materials.*

Part Name	**Orig. material**	**New material**	**Manuf. process**	**Weight (g)**
Base	Aluminum	HDPE	Injection molding	63.75
Base cover	SBR rubber	NBR rubber	Injection molding	25.33
Handle	HDPE	LDPE	Injection molding	40.17
Magazine	Low-carbon steel	Stainless steel	Extrusion	52.8



Environmental Impact (calculated using CML impact assessment methodology)

Carbon Footprint

🟦 Material:	0.796 kg CO_2e
🟨 Manufacturing:	0.149 kg CO_2e
🟧 Use	0.00 kg CO_2e
🟪 Transportation:	0.058 kg CO_2e
▢ End of Life:	0.324 kg CO_2e

1.3 kg CO_2e

Energy Consumption

🟦 Material:	16 MJ
🟨 Manufacturing:	2.8 MJ
🟧 Use	0.00 MJ
🟪 Transportation:	0.852 MJ
▢ End of Life:	0.252 MJ

20 MJ

Air Acidification

🟦 Material:	2.3E-3 kg SO_2e
🟨 Manufacturing:	9.4E-4 kg SO_2e
🟧 Use	0.00 kg SO_2e
🟪 Transportation:	2.7E-4 kg SO_2e
▢ End of Life:	2.6E-4 kg SO_2e

3.7E-3 kg SO_2e

Water Eutrophication

🟦 Material:	1.2E-3 kg PO_4e
🟨 Manufacturing:	3.5E-5 kg PO_4e
🟧 Use	0.00 kg PO_4e
🟪 Transportation:	6.1E-5 kg PO_4e
▢ End of Life:	5.5E-5 kg PO_4e

1.4E-3 kg PO_4e

Figure 4.14: SolidWorks environmental impacts of the stapler with new materials.

The perturbations in the four components have caused important changes in the analytical results. Appendix C shows the three diagrams used to analyze the environmental impacts of the stapler in GaBi and the next four figures, Figure 4.15, Figure 4.16, Figure 4.17, and Figure 4.18 display the environmental impacts of the new stapler provided by GaBi Education.

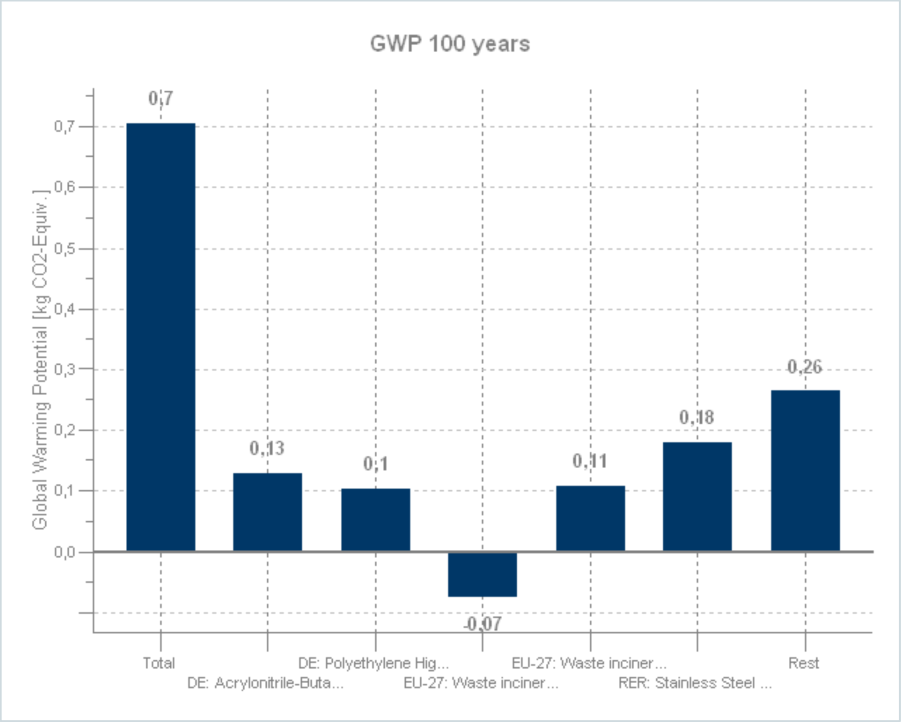


Figure 4.15: Carbon impacts of the redesigned stapler.

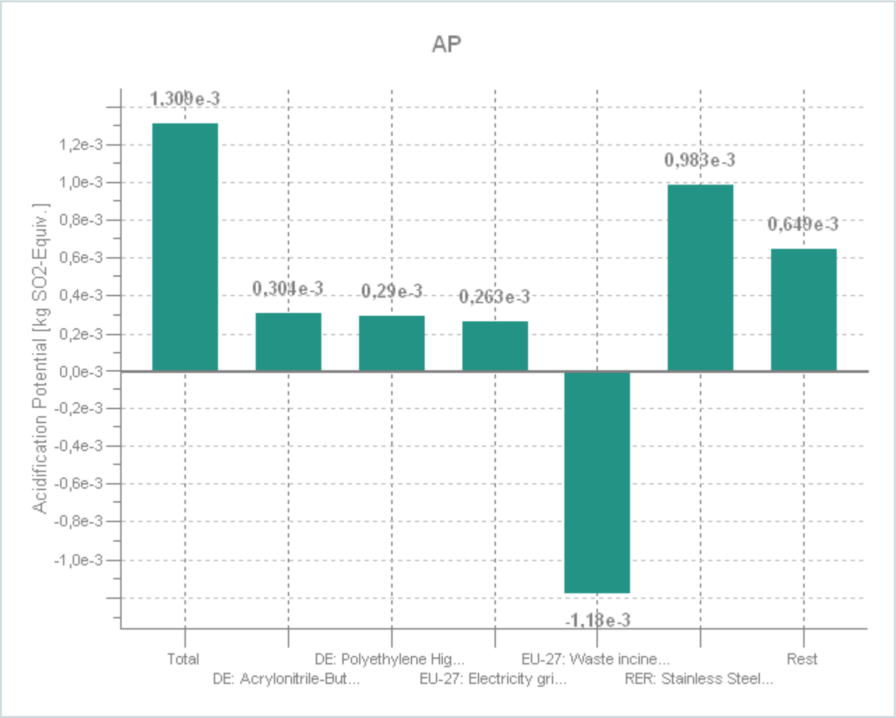


Figure 4.16: Air acidification impacts of the redesigned stapler.

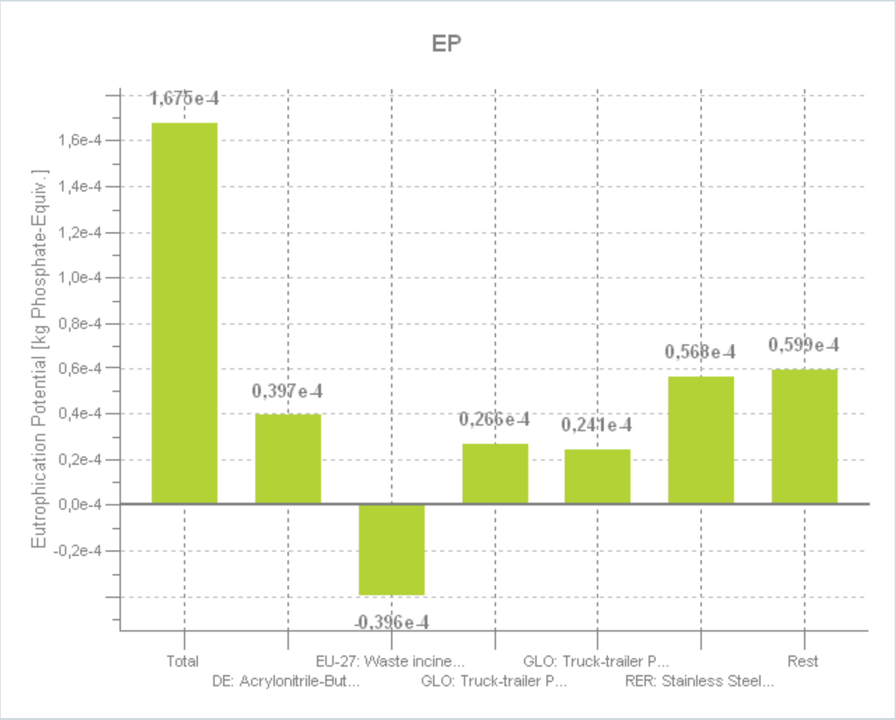


Figure 4.17: Water eutrophication impacts of the redesigned stapler.

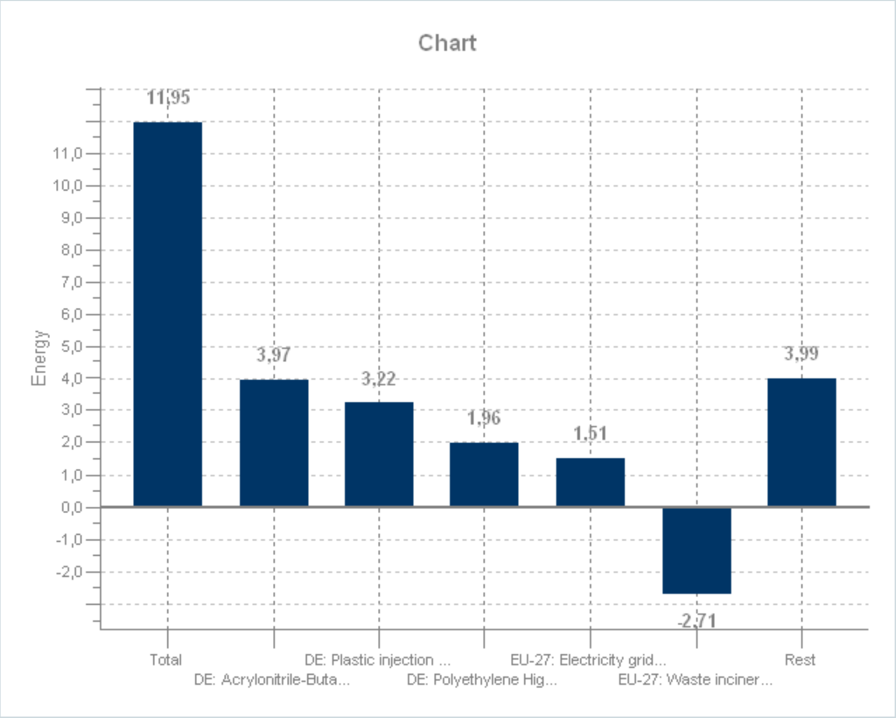


Figure 4.18: Energy consumption of the redesigned stapler.

Along with the comparison of the GaBi analytical results with the SolidWorks Sustainability results, Table 4.12 shows separately the percentage of change of the GaBi and SolidWorks results from the original stapler from section 4.2 to the new version of the stapler with the edited materials.

As it was expected, both GaBi and SolidWorks provide smaller numerical results for the environmental impacts of the new stapler. This overall environmental impact diminution is related to the substantial weight reduction of the stapler's materials. The only impact that is bigger in the new stapler is the SolidWorks water impact, increasing from 0.00083 Kg PO_4e in the original stapler to 0.0014 Kg PO_4e in the new stapler.

It is possible to affirm that the stapler's comparison has revealed that the new stapler configuration offers a reduction in the ecological footprint of the product and therefore, the new stapler offers a more sustainable product than the original stapler.

However, when comparing GaBi's results with SolidWorks' results, it is still noticeable that the results are reasonably different, as it previously occurred when analyzing the original stapler in section 4.2. The estimated +/- 20% margin of error is not maintained in any of the stapler's analyses.

Table 4.12: *Comparison of the staplers' analytical results.*

Impact	**GaBi 1**	**GaBi 2**	**Dif. GaBi**	**SW 1**	**SW 2**	**Dif. SW**
Kg CO_2e	2.17	0.7	-67.74%	3.4	1.3	-61.76%
Kg SO_2e	0.011	0.001309	-88.1%	0.019	0.0037	-80.52%
Kg PO_4e	0.0005665	0.0001675	-70.43%	0.00083	0.0014	+68.67%
MJ	50.89	11.95	-76.52%	41	20	-51.22%

In regards to comparing how the analytical results of the two different LCA programs have individually evolved, the difference in the results seems to be smaller than when comparing GaBi to SolidWorks. For example, the total energy has decreased a 76.52% in GaBi to a 51.22% in SolidWorks Sustainability, providing a 25% difference. The carbon and air impacts have respectively decreased a 67.74% and a 88.1% in Gabi to a 61.76% and a 80.52% in SolidWorks, resulting in a less than 10% difference. Only the water impacts do not present any kind of similarity, as SolidWorks Sustainability gives a bigger value of kilograms of PO_4 to the new stapler.

4.4 Chapter summary

In this section, SolidWorks Sustainability has been tested and compared to GaBi through three different analyses. The software has been firstly examined with isolated parts (section 4.1). In this section five different parameters (raw material, manufacturing, use region, transportation, and end of life scenario) have been tested using simple inputs.

The material stage is the stage with the best results in terms of maintaining the estimated margin of error. In the manufacturing stage only half of the analytical results maintained the estimated margin of error. The environmental impacts associated to the transportation scenario result in very small values and are very hard to compare. However, better results are provided when the fuel type is not taken into account in the comparison, meaning that the lack of fuel specification in SolidWorks Sustainability makes the software imprecise. The use section has not been compared between GaBi and SolidWorks Sustainability because SolidWorks presents a totally different approach.

Finally, the end of life scenario presents a more comprehensive analysis in GaBi than in SolidWorks as SolidWorks only offers three end-of-life options to choose from.

Section 4.2 analyzed the environmental impacts of an assembly (a regular-sized stapler). The comparison of the analytical results from GaBi and SolidWorks concluded that only the total energy satisfies the +/- 20% margin of error. For the rest of the impacts, SolidWorks provides a higher value than GaBi.

Section 4.3 included the results of the regular-sized stapler being exposed to different perturbations. These perturbations helped to understand the software performance more profoundly. The change in shape perturbation demonstrated that SolidWorks Sustainability does not perform environmental analyses of products based on their shape or volume, but based in the materials' weight. The second perturbation consisted of a change of materials. All the impacts in GaBi and in SolidWorks except for the eutrophication impacts present smaller impacts for the redesigned stapler. Overall, all the analyses helped to identify the possible benefits and limitations of using a 3D modeling software as a tool to perform an LCA.

CHAPTER 5. CONCLUSIONS

As a result of constant growing environmental concerns, the need for procedures capable of improving the environmental impacts of products has become a priority for many industries. Significant gaps revealed a lack of implementation of environmental requirements in early product design. New emerging CAD software able to integrate environmental requirements as part of the product design process is being developed for non-LCA expert designers. Due to this new variety of techniques, the environmental analyses and the level of accuracy of those compared to the traditional analyses performed by dedicated LCA software can vary considerably.

The principal goal of the research was to identify how the numerical results associated to the typical major stages of an LCA (material extraction, manufacturing, usage, transportation, and end of life scenario) performed by a CAD software tool differ with respect to the numerical results provided by a traditional LCA. It was also important to examine the main advantages and drawbacks of using a CAD software tool, in this specific case SolidWorks Sustainability, as a software for performing environmental analyses of products and processes.

This chapter explains the main findings from the comparison of SolidWorks Sustainability and GaBi Education as well as some limitations of the research. Finally, the chapter will discuss possible areas of future research.

5.1 Findings and conclusions

After all the data gathering and data analyses obtained from chapter four, it is possible to affirm that the analytical results of an LCA performed by a CAD software tool differ considerably with respect to the results provided by a dedicated LCA software. All the analyzed variables (carbon footprint, acidification impacts, eutrophication impacts, and energy consumption) present substantial differences when the analytical results of both programs are compared.

Nevertheless, the usage of a CAD software tool as a tool to perform an LCA can bring some several benefits when environmental requirements are introduced into the product development process. The most important findings from the data analyses are summarized as follows:

- The lack of specific data such as material type or energy used in the manufacturing processes has led to the use of generic predefined data and manufacturing processes in both GaBi and SolidWorks. GaBi Education offers fully functional software for students but the available database is not as extensive and robust as the Professional database. In addition, in SolidWorks Sustainability there is limited data to pick from, making the software comparison more difficult as the input data is hard to match.
- GaBi has a steep learning curve, making the learning process very time-consuming. Inversely, SolidWorks Sustainability is exceptionally user friendly and easy to get started with.
- Even though SolidWorks Sustainability assures that its results should be only used as an estimate, it also assures that the values in SolidWorks Sustainability

when compared to GaBi are useful to within +/- 20%. The several analyses carried out throughout the analysis confirm that the +/-20% estimated margin of error is not being maintained. Therefore, the product does not support the initial specifications and it is advertised to SolidWorks Sustainability users without being as accurate as it is supposed to be.

- The best results in terms of accuracy are found in the material comparison (section 4.1.1). This is because the material stage is normally the stage where the major environmental impacts occur; thus, the numerical results of the environmental impacts are bigger and derived errors from the comparison are smaller. In addition, the material section is the first section to be selected in SolidWorks Sustainability and it remains unaffected by other processes such as manufacturing or transportation. When analyzing other stages, the margin of error will keep increasing as the product comparison already starts with different inputs. Some input data such as electricity consumption or payload of the transportation vehicle are also impossible to match in SolidWorks Sustainability as the data remain unknown or because the option to add this type of information in the CAD software does not exist.
- The results give evidence that the percentage of error is lower when the fuel type in the transportation stage is not taken into account. For this, it is possible to affirm that the lack of fuel specification in SolidWorks Sustainability makes the software more inaccurate.
- Results from this study revealed that different shapes or different geometric characteristics in design do not affect the performance and outcome of

SolidWorks Sustainability. As it happens in traditional LCA software, SolidWorks Sustainability analyzes the products based exclusively on the product's mass.

- SolidWorks Sustainability is designed as a comparison tool and as an indicator of environmental improvement. It is a very useful tool when the main purpose of the study is to compare different products with the same software. The most consistent way to use SolidWorks Sustainability or any other similar CAD-integrated tool is to set a product as a baseline and then track the changes from the original product to the new version of the product.

5.2 Discussion

Environmental concerns are becoming an important issue in the forthcoming years, as specific materials become scarcer and environmental regulations and legislations become stricter. Designers need to be aware of the environmental impacts of the whole life cycle of their products in order to comply with growing product standards. If products do not meet those legislative standards, legal actions can condition the market access to the products. In addition, the introduction of environmental requirements in early product development can help companies and designers to convert legislative controls into financial benefits and societal recognition. The idea of bringing LCA data into product design software is very appealing, but very few CAD tools offering LCA features are available at the moment. The study aimed to demonstrate that SolidWorks Sustainability is an innovative tool that reduces the traditional hurdles to sustainable design.

The analyses in chapter four revealed that the accuracy of SolidWorks Sustainability is not precise enough when comparing the SolidWorks' analytical results to GaBi's results.

As Morbidoni et al. (2011) claimed, these new CAD-integrated tools offer the possibility for designers to introduce environmental information in their designs, but errors and lack of data are still present in this type of software.

Luttropp and Lagerstedt (2006) illustrated in Figure 2.1 how the environment should be merged into product development processes. SolidWorks Sustainability integrates environmental information in the product design, however other product's demands related to the concept of sustainability such as economic requirements or social responsibility are still lacking. In addition, the restricted data in their databases and the limited quantity of environmental impacts makes the software still incomplete (Ostad-Ahmad-Ghorabi et al., 2009). Therefore, a good start to make SolidWorks Sustainability a more complete CAD-integrated LCA tool would be to make the software more predictive. SolidWorks Sustainability has the potential of becoming more predictive if more information and databases were available. More tests, analyses, and iterations with different datasets would help validate the new approach. In addition, LCA experts should get involved in the process to interpret and refine the software with the required corrections. Thus, SolidWorks Sustainability would become a more useful and accepted simplified LCA tool.

In conclusion, at the present time SolidWorks Sustainability works as a trade-off solution incorporating sustainability features into early product design and it helps designers moving towards greener and smarter product design. The integrated sustainability features make SolidWorks positively differentiate and stand out from other CAD programs, yet, due to the poor LCA performance, the sustainability feature should be integrated at no additional charge in any SolidWorks version as an environmental comparative tool.

Designers should be aware that SolidWorks Sustainability does not provide an extensive and evaluative analysis of a product the same way a complete LCA does, but at least it allows designers to preview what possible environmental impacts their products will have throughout an iterative and exploratory process. As Russo et al., (2014) stated, a complete LCA requires a general process model, which is currently not embedded in SolidWorks Sustainability, therefore designers should use SolidWorks Sustainability exclusively as an environmental impact dashboard. Even though the results of this thesis are specific to SolidWorks Sustainability, the software outcomes have demonstrated that dedicated LCA software and CAD-integrated LCA software, should not be used as substitutes and for the moment, these software tools should be used with different purposes.

5.3 Recommendations for Future Research

More and more frequently, the environmental impacts of products and the environmental impacts of industrial processes are becoming an important factor of design selection. In order to further improve the sustainable properties of product development, designers need to understand the environmental impacts of their products.

This study aimed to demonstrate that recent CAD tools that integrate environmental features are user-centered but do not meet the needs in terms of environmental analysis performance.

Further research would be necessary to decide if improved CAD tools will be able to meet the needs of designers including environmental requirements into product development processes. A more detailed analysis using different products and different settings, such as different geographic regions or different transportation distance, would help to better understand the performance of SolidWorks Sustainability.

The majority of the assessed components in all the performed analyses are very lightweight and consequently, the numerical results of the environmental impacts associated to those parts are very small. Analyzing much heavier components and products would benefit the comparison of numerical results, as the environmental impacts would have a bigger order of magnitude and small variations in the results would not affect the margin of error severely.

This thesis has focused on analyzing the SolidWorks Sustainability results with the GaBi results. Comparing the GaBi analytical results with the results of another dedicated LCA software would help to recognize and understand if variability in results also exists when comparing results from different dedicated LCA software. Also and in order to make the analyses more precise and to increase the transparency of the GaBi environmental results before comparing them to SolidWorks Sustainability, it would be interesting to quantify the uncertainties of the results with a statistical tool, such as GaBi Analyst.

Finally, even though there are just a few available CAD programs able to perform environmental analyses, a more complete comparative study of SolidWorks Sustainability with other LCA-integrated CAD software would bring sharper conclusions about the accuracy of SolidWorks Sustainability.

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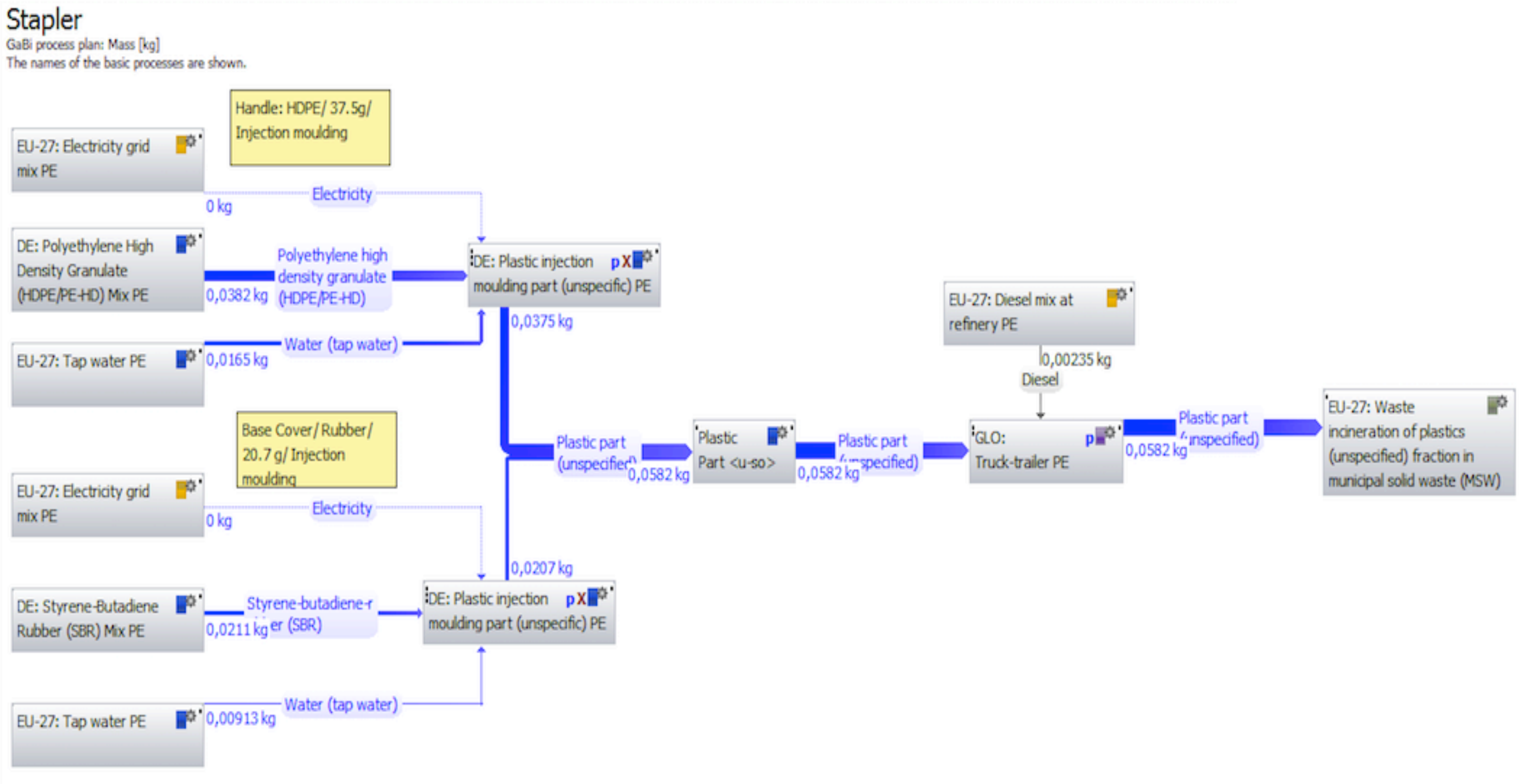
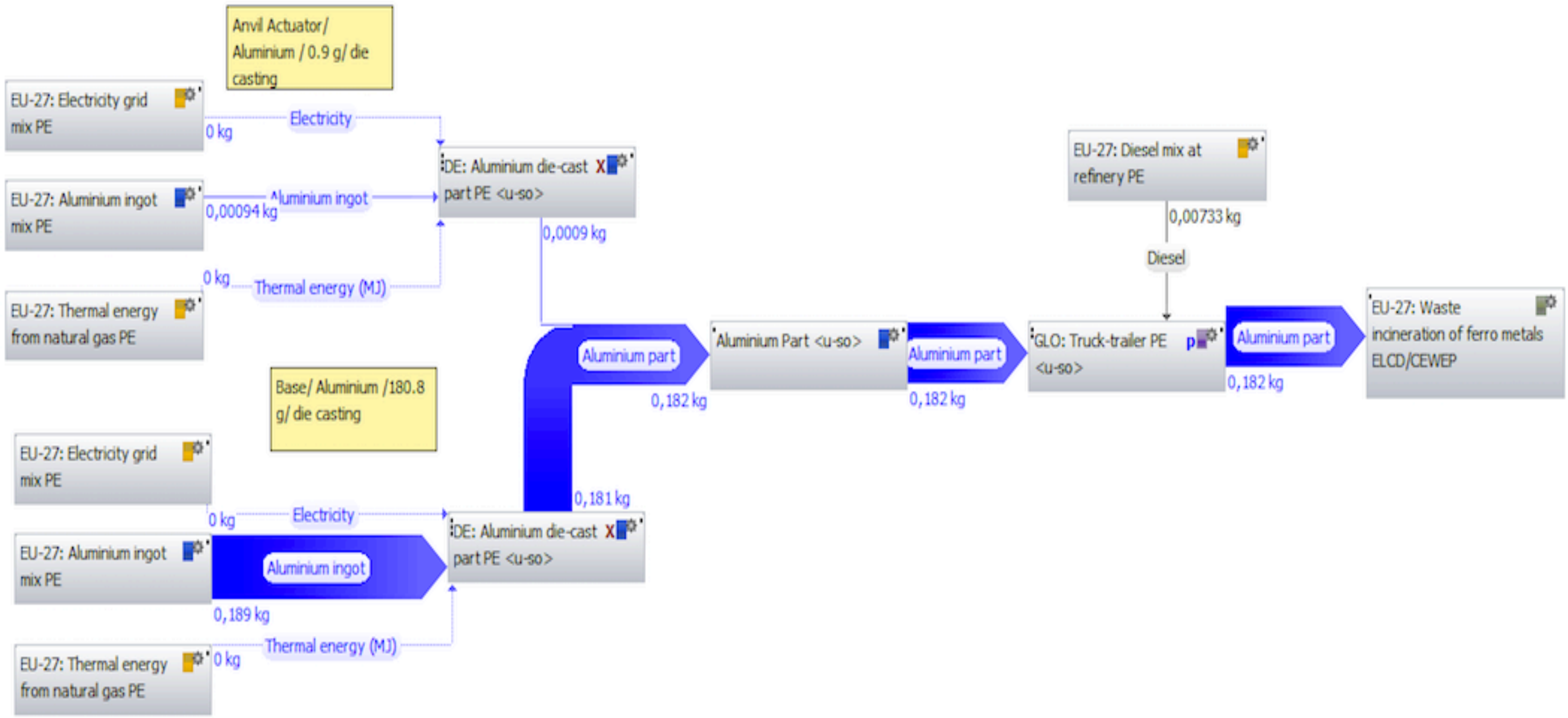
APPENDICES

Appendix A Gabi process plan: Stapler

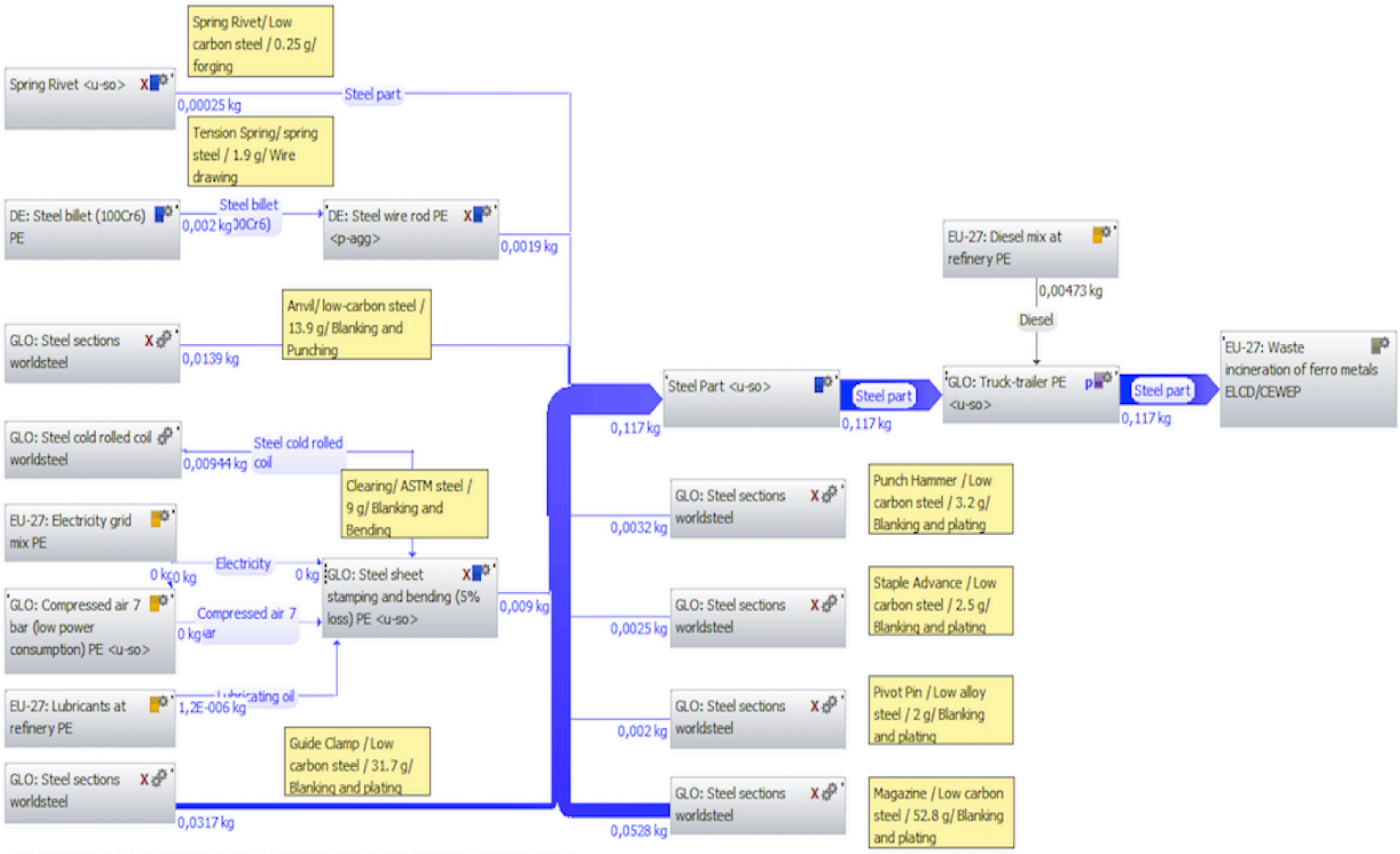
Plastic Parts:



Aluminum Parts:

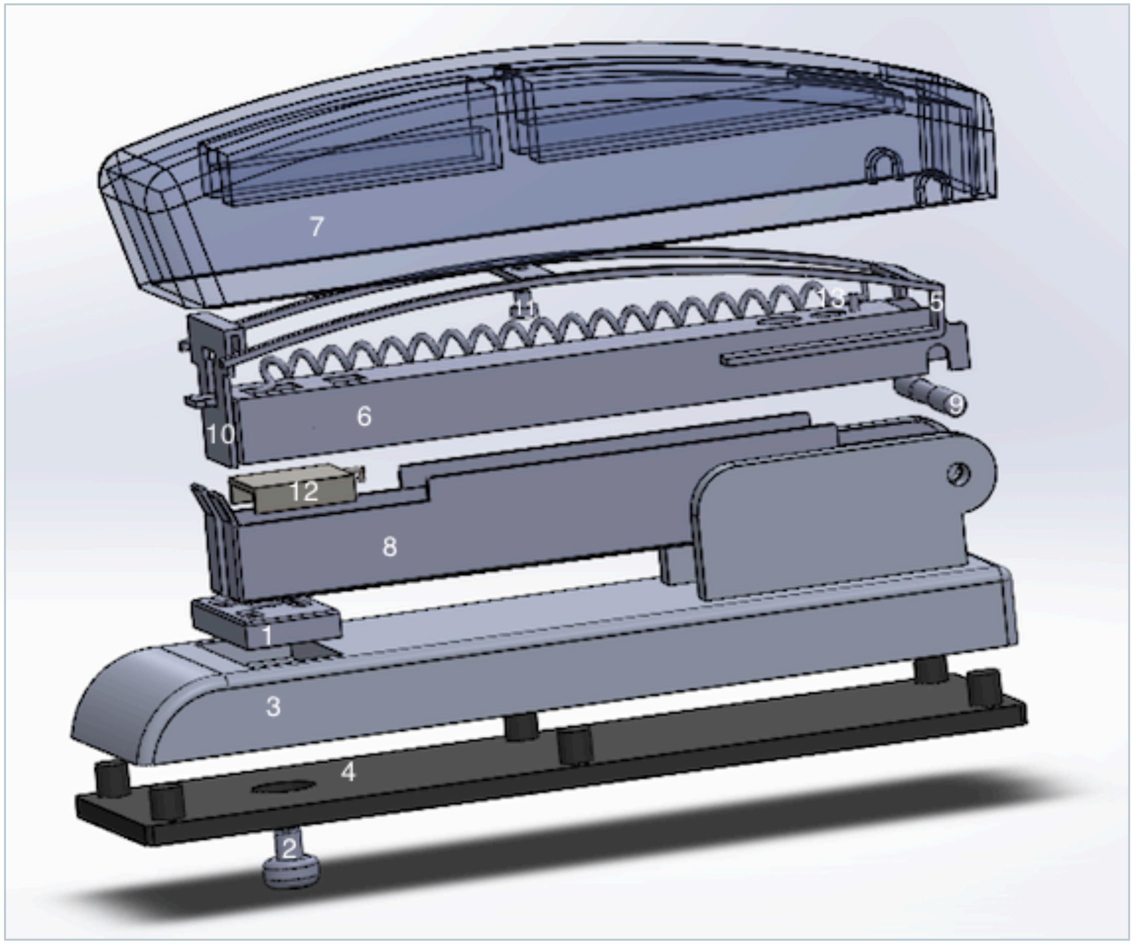


Steel Parts:



Spring Rivet <u-so>
Spring Rivet/ Low carbon steel / 0.25 g/ forging
Steel part
0,00025 kg
Tension Spring/ spring steel / 1.9 g/ Wire drawing
DE: Steel billet (100Cr6) PE
Steel billet
0,002 kg (100Cr6)
DE: Steel wire rod PE <p-agg>
0,0019 kg
GLO: Steel sections worldsteel
0,0139 kg
Anvil/ low-carbon steel / 13.9 g/ Blanking and Punching
GLO: Steel cold rolled coil worldsteel
Steel cold rolled coil
0,00944 kg
Clearing/ ASTM steel / 9 g/ Blanking and Bending
EU-27: Electricity grid mix PE
Electricity
0 kg
GLO: Steel sheet stamping and bending (5% loss) PE <u-so>
0,009 kg
GLO: Compressed air 7 bar (low power consumption) PE <u-so>
Compressed air 7 bar
0 kg
EU-27: Lubricants at refinery PE
Lubricating oil
1,2E-006 kg
Guide Clamp / Low carbon steel / 31.7 g/ Blanking and plating
GLO: Steel sections worldsteel
0,0317 kg
0,117 kg
Steel Part <u-so>
Steel part
0,117 kg
EU-27: Diesel mix at refinery PE
0,00473 kg
Diesel
GLO: Truck-trailer PE <u-so>
Steel part
0,117 kg
EU-27: Waste incineration of ferro metals ELCD/CEWEP
GLO: Steel sections worldsteel
0,0032 kg
Punch Hammer / Low carbon steel / 3.2 g/ Blanking and plating
GLO: Steel sections worldsteel
0,0025 kg
Staple Advance / Low carbon steel / 2.5 g/ Blanking and plating
GLO: Steel sections worldsteel
0,002 kg
Pivot Pin / Low alloy steel / 2 g/ Blanking and plating
GLO: Steel sections worldsteel
0,0528 kg
Magazine / Low carbon steel / 52.8 g/ Blanking and plating

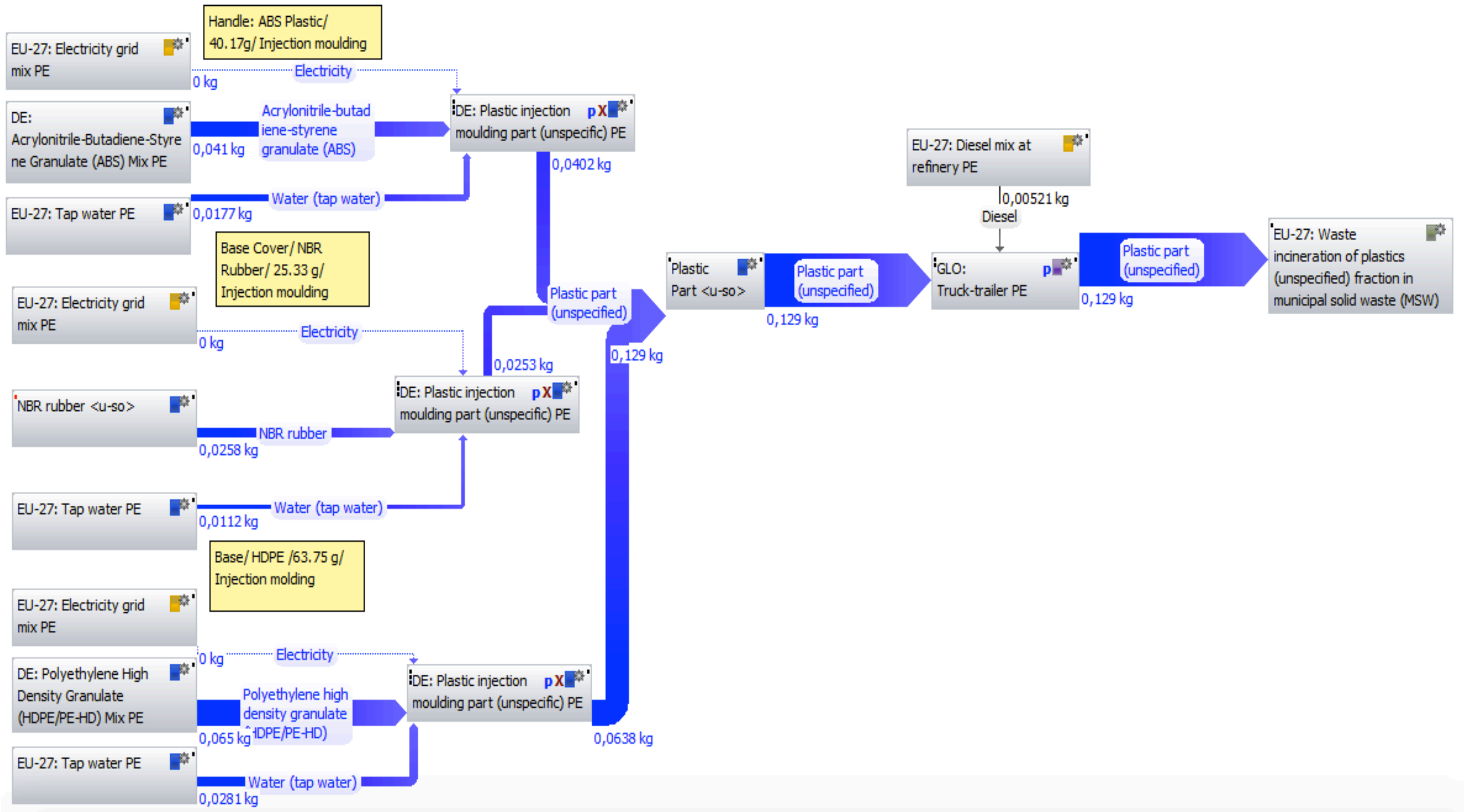
Appendix B SolidWorks process plan: Stapler



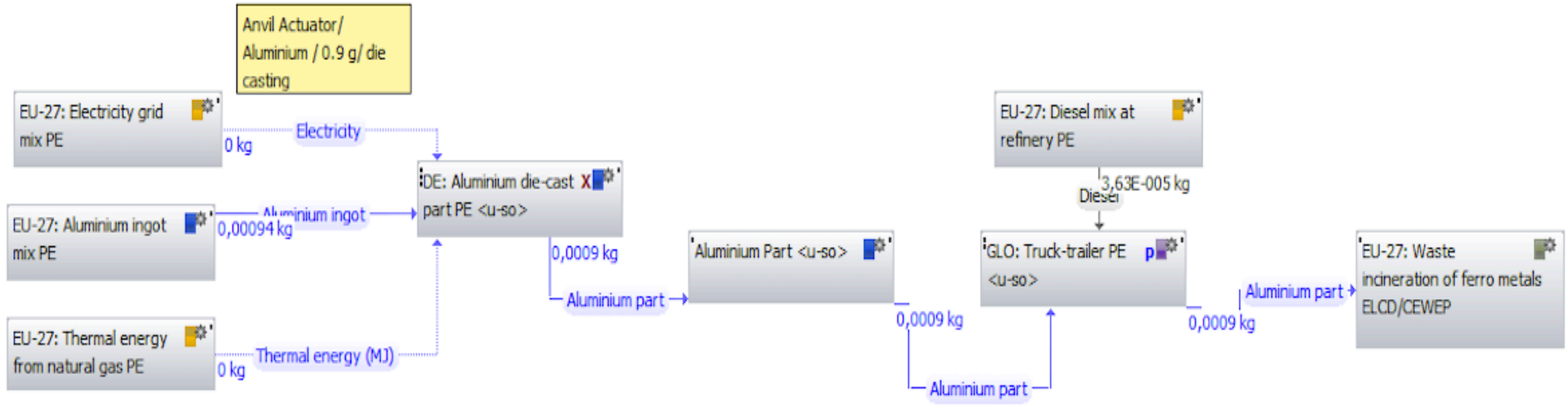
1. Anvil
2. Anvil actuator
3. Base
4. Base cover
5. Clearing
6. Guide clamp
7. Handle
8. Magazine
9. Pivot pin
10. Punch/hammer
11. Spring Rivet
12. Staple advance
13. Tension spring

Appendix C GaBi process plan: Stapler with new materials

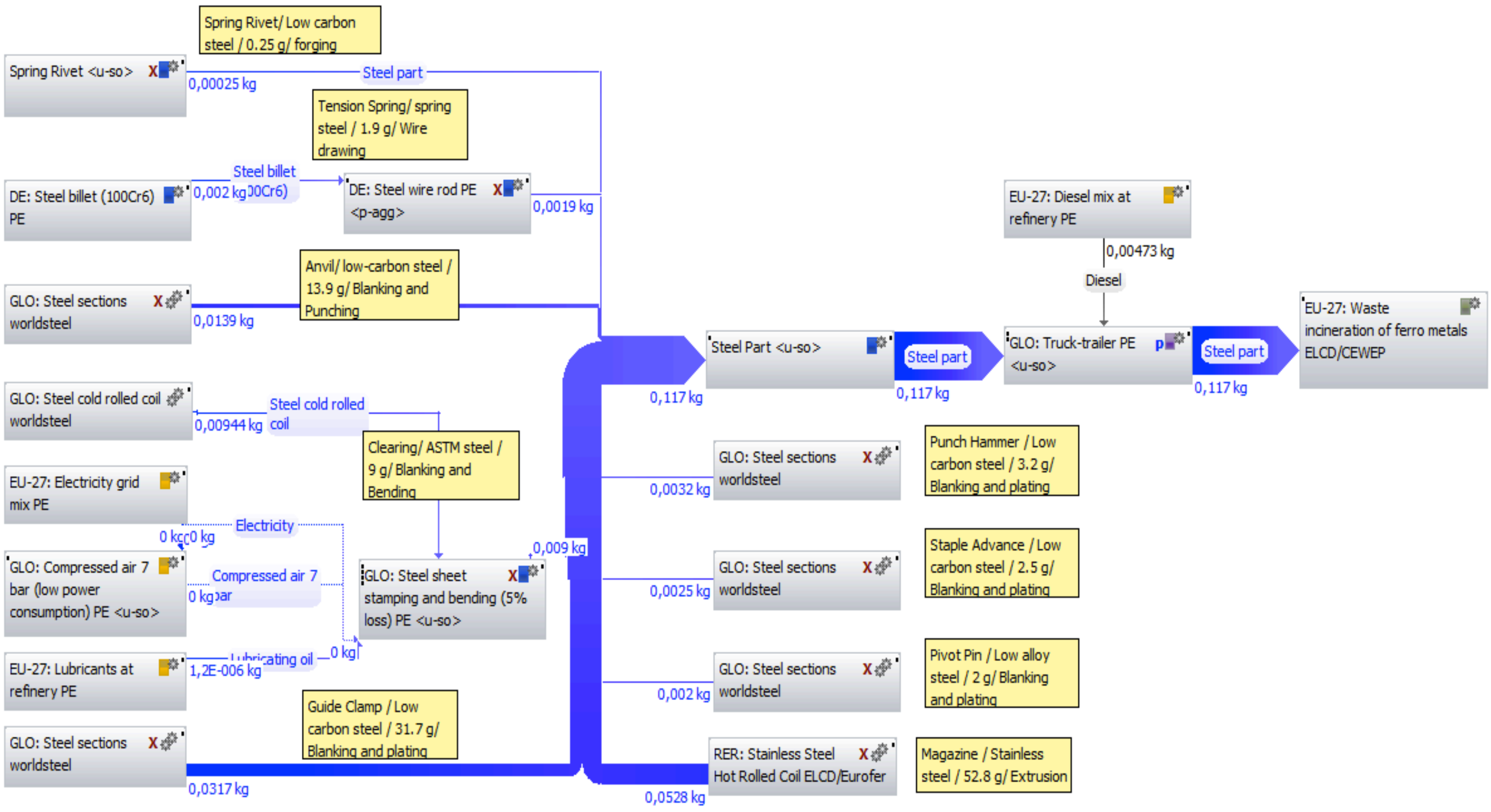
Plastic Parts:



Aluminum Parts:



Steel Parts:


Spring Rivet/ Low carbon steel / 0.25 g/ forging
Spring Rivet <u-so>
0,00025 kg
Steel part
Tension Spring/ spring steel / 1.9 g/ Wire drawing
DE: Steel billet (100Cr6) PE
0,002 kg
Steel billet
DE: Steel wire rod PE <p-agg>
0,0019 kg
Anvil/ low-carbon steel / 13.9 g/ Blanking and Punching
GLO: Steel sections worldsteel
0,0139 kg
GLO: Steel cold rolled coil worldsteel
0,00944 kg
Steel cold rolled coil
Clearing/ ASTM steel / 9 g/ Blanking and Bending
EU-27: Electricity grid mix PE
Electricity
0 kg
0 kg
GLO: Compressed air 7 bar (low power consumption) PE <u-so>
Compressed air 7 bar
0 kg
GLO: Steel sheet stamping and bending (5% loss) PE <u-so>
0,009 kg
EU-27: Lubricants at refinery PE
1,2E-006 kg
Lubricating oil
0 kg
Guide Clamp / Low carbon steel / 31.7 g/ Blanking and plating
GLO: Steel sections worldsteel
0,0317 kg
Steel Part <u-so>
0,117 kg
Steel part
0,117 kg
EU-27: Diesel mix at refinery PE
0,00473 kg
Diesel
GLO: Truck-trailer PE <u-so>
Steel part
0,117 kg
EU-27: Waste incineration of ferro metals ELCD/CEWEP
GLO: Steel sections worldsteel
0,0032 kg
Punch Hammer / Low carbon steel / 3.2 g/ Blanking and plating
GLO: Steel sections worldsteel
0,0025 kg
Staple Advance / Low carbon steel / 2.5 g/ Blanking and plating
GLO: Steel sections worldsteel
0,002 kg
Pivot Pin / Low alloy steel / 2 g/ Blanking and plating
RER: Stainless Steel Hot Rolled Coil ELCD/Eurofer
0,0528 kg
Magazine / Stainless steel / 52.8 g/ Extrusion