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## Cost and Environmental Impacts in Manufacturing: A Case Study Approach

Nils Nörmann  
University of Rhode Island, n.noermann@gmail.com

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COST AND ENVIRONMENTAL IMPACTS IN MANUFACTURING: A CASE  
STUDY APPROACH

BY

NILS NÖRMANN

A THESIS SUBMITTED IN PARTIAL FULFILLMENT OF THE  
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IN

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2015

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OF  
NILS NÖRMANN

APPROVED:

Thesis Committee:

Major Professor: Valerie Maier-Sperdelozzi  
Yi Zheng  
Aaron S. Bradshaw  
Nasser H. Zawia  
DEAN OF THE GRADUATE SCHOOL

UNIVERSITY OF RHODE ISLAND  
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## **ABSTRACT**

According to the Brundtland report, sustainable development “meets the needs of the present without compromising the ability of future generations to meet their own needs” (United Nations 1987). The 3 pillars of sustainability have been identified as economic development, social development, and environmental protection (United Nations 2005). These components interact and affect each other in any real world application. For manufacturing companies, sustainable manufacturing is one way to decrease the environmental impact of their products. In the literature, there are different approaches to assess sustainability. However, no approach aims to improve sustainability and costs since sustainability and cost reduction are often seen as conflictive and cannot be achieved at the same time. An overlap between cost reduction and sustainability can push companies to expend more effort in order to achieve long term business success while decreasing the environmental impact of their products.

This study presents a framework that aims to prove this overlap based on gathered data of a case study. Besides an assessment of the current state of manufacturing processes, alternative future state models are determined, which are more sustainable and decrease the costs of production.

All data gathered within this study was manipulated by a key multiplier to ensure the integrity of the manufacturer and does not represent the real manufacturing data.

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## LIST OF ABBREVIATIONS

ABC	Activity Based Costing
AP	Acidification Potential
BOM	Bill of Material
BTU	British Thermal Unit
CACE	Computer Aided Cost Estimation
CAD	Computer Aided Design
CFH	Cubic Foot Per Hour
CNC	Computer Numerical Control
CSD	Commission on Sustainable Development
DALY	Disability Adjusted Life Years
DCB	Dichlorobenzene
DFA	Design for Assembly
DFE	Design for Environment
DFM	Design for Manufacturing
DFMA	Design for Manufacture and Assembly
DFX	Design for X
DIN	German Institute for Standardization
EIA	Energy Information Administration
ELCD	European Reference Life Cycle Database
EPA	Environmental Protection Agency

GMA	Grocery Manufacturers Association
GMAW	Gas Metal-Arc Welding
GWP	Global Warming Potential
HAP	Hazardous Air Pollutants
HT	Human Toxicity
IEU	Industrial Equipment Unit
ISO	International Organization for Standardization
LCA	Life Cycle Assessment
LCI	Life Cycle Inventory
LCIA	Life Cycle Impact Assessment
MECS	Manufacturing Energy Consumption Survey
MIG	Metal Inert Gas Welding
MTM	Methods Time Measurement
NEEDS	New Energy Externalities Developments for Sustainability
NERC	North American Electric Reliability Corporation
NREL	National Renewable Energy Laboratory Data Base
PLI	Physical Load Index
PVC	Polyvinyl chloride
SLCA	Simplified Life Cycle Assessment
SMAW	Shielded Metal-Arc Welding
Sus-VSM	Sustainable VSM
VOC	Volatile Organic Compound

VSM

Value Stream Map



## **CHAPTER 1 – INTRODUCTION**

This thesis provides an overview of the broad discussed topic of sustainability and assessment of sustainability in manufacturing by means of an extensive literature review. Furthermore, a framework to relate manufacturing costs to environmental impact will be derived and applied to a case study at a manufacturing company. The first section of this chapter presents the background of the study and exposes the gaps and concerns that justify the research in this field. The second section describes the derived objectives of this study and how they can be approached successfully.

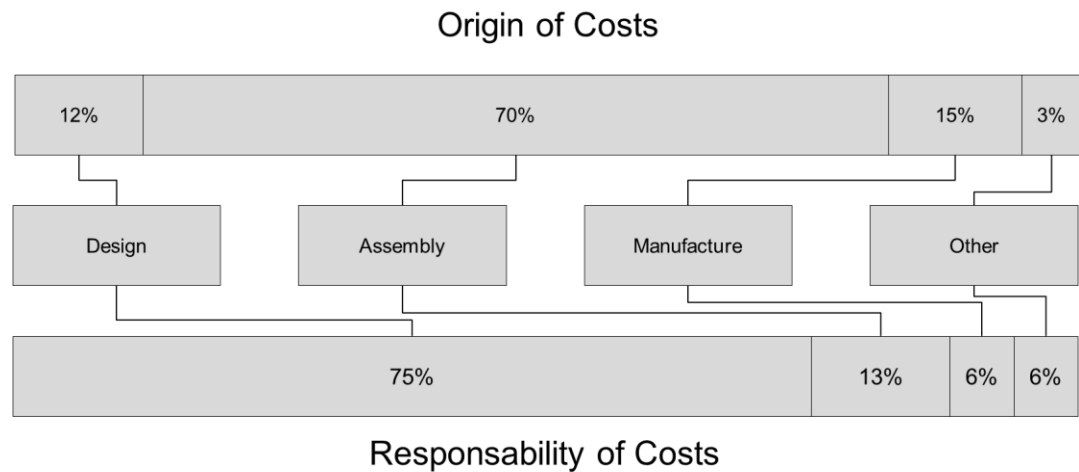
### **1.1. Background, Motivation and related Problems**

A study of The Grocery Manufacturers Association (GMA) and Deloitte from 2009 states that 95% of all customers would buy “green products”, if there is a satisfactory product on the market. Compared to the 25% of customers who already purchase green products, it derives that there is an unfulfilled demand for such products on the market. This survey shows, that nowadays the demand for sustainable products show that society is more aware of the increasing pollution in the environment and how it is connected to the ways products are made (Deloitte 2009). Customers are increasingly environmentally conscious in their purchase decisions, putting more pressure on the producers to create more sustainable products (Windsor 2011). In addition to this, environmental legislation is becoming stricter in order to

extend the producer's responsibility (Lindahl 2006). To fulfill customer desires and current environmental laws, companies have to redesign their products and still stay competitive within the market. Therefore, the costs of the products have to be kept on the same level or decrease within the redesign process. While different techniques such as Design for Environment (DFE) and Design for Sustainability aim to decrease the environmental impact of a product, Design for Cost aims to decrease the costs of a product. This thesis will analyze the different techniques in order to identify whether the relationship between sustainability and cost reduction is in conflict, or if there are overlapping benefits. The outcome of this approach will be a verification of the existing overlapping benefits and how they can be achieved. Furthermore, to prove these findings a case study in cooperation with a regional company is considered. An existing product will be chosen and reasonable assumptions will be made in order to verify the hypotheses. The overlap of sustainability and cost reduction would also mean an overlap in business and stakeholder interest and protection of the environment. Proving this overlap can push companies to expend more effort in order to achieve long term business success while decreasing the environmental impact of their products (Savitz and Weber 2007).

In a world with limited resources and increasing pollution problems a more sustainable environment is highly important (Ljungberg 2007). In order to contribute to this idea more sustainable products are needed, which means new ecofriendly designs have to be implemented. To help designers and engineers, different types of methods have been developed to support the development process with guidelines for sustainability. However, price is one of the most important characteristics for a

successful product since most customers are price sensitive. Therefore, it can be difficult to design a successful product while only focusing on its sustainability. To avoid higher prices, reducing costs is one of the most important goals for every company. Lean design processes that aim to reduce the cost of the product are indispensable, since the early stages of product development the influence of future costs is high (see Figure 1) (Bullinger and Warschat 1995).

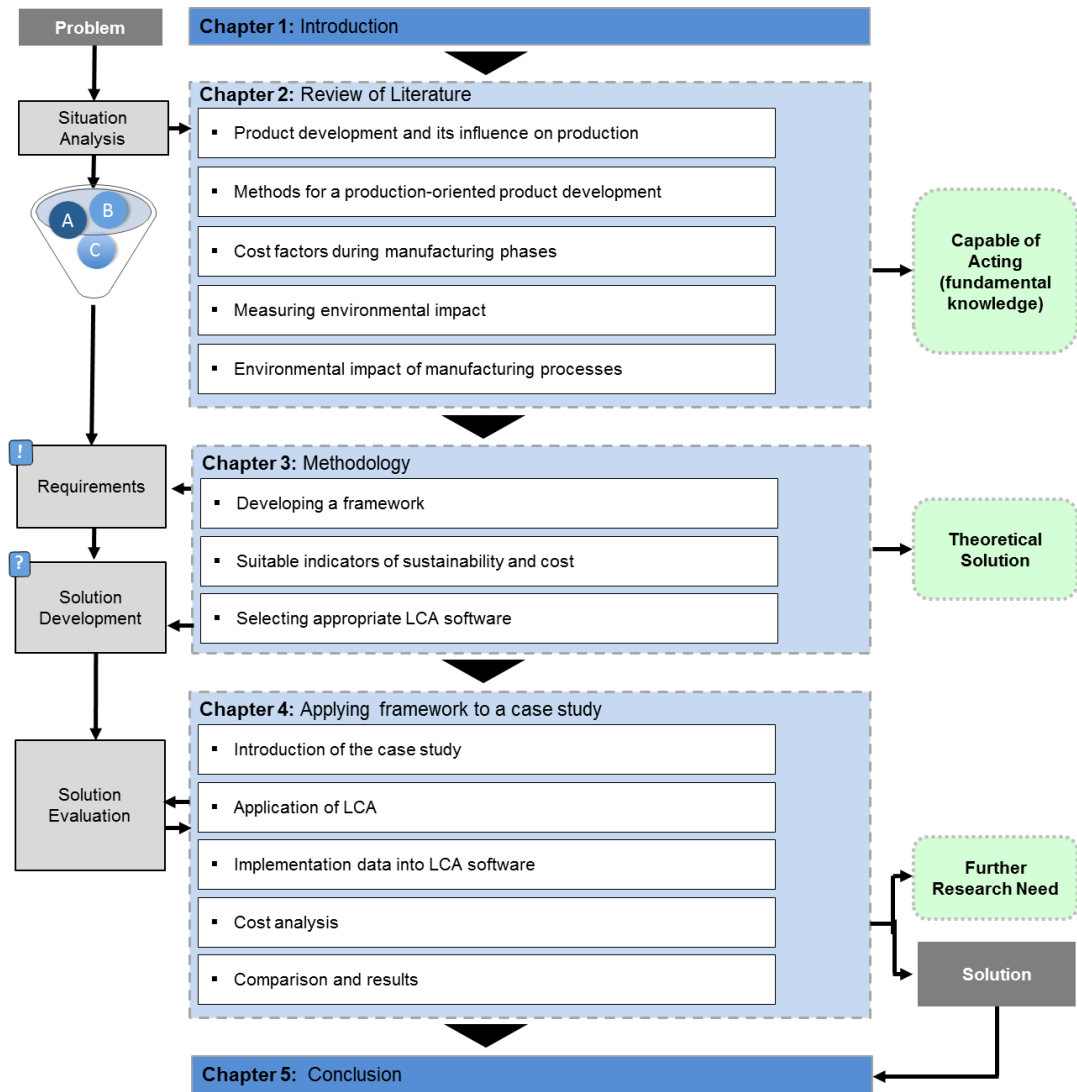


**Figure 1: Comparison of Origin and Responsibility of Costs (Bullinger and Warschat 1995)**

## **1.2.Objectives and Procedure**

While sustainability and cost reduction are both well researched, a comprehensive approach of how to combine these two terms is missing. Therefore, this research study aims to analyze overlap of sustainability and cost based on a case study conducted at a manufacturing company. This analysis identifies where in the manufacturing process most of the environmental impact is caused and compares them with costs. Finally, this study aims to provide alternative routings and processes to decrease the environmental impact and costs. The procedures followed in this research study are

illustrated in Figure 2 and are oriented toward the problem-solving cycle. According to these procedures, the problem is formulated in the first chapter.



**Figure 2: Overall procedures of the study**

In the next chapter, an extensive literature review is given to provide fundamental knowledge of:

- Manufacturing and product development
- Cost and environmental impact factors in manufacturing
- Sustainable manufacturing

Manufacturing and product development stresses on different approaches of how to decrease manufacturing costs and enhance sustainability in the early stages of the product design. Cost in manufacturing aims to explain the different cost factors in manufacturing that are related to environmental impact and how to estimate them. Whereas sustainable manufacturing explains different methods of measuring the environmental impact of manufacturing processes and gives an overview of different manufacturing processes and their environmental impact.

The third chapter introduces presents the methodology that is used in this research to develop a framework to combine costs and environmental impacts. This includes the identification of suitable measures for environmental impact and sustainability, the evaluation of different software tools and how the results can be visualized and compared to costs. In the fourth chapter, based on the framework, a case study is conducted at a manufacturing company to assess the environmental impact of a specific product. Therefore, Life Cycle Assessment (LCA) which is a common method to evaluate the environmental impact of a product during its life cycle. Possible results are for example the total CO<sub>2</sub> emissions that are released within the manufacturing process. In the next step alternative manufacturing routing and product designs are suggested and evaluated. By comparing the LCA results of each alternative the most environmental design and manufacturing process can be derived. Furthermore, the LCA results will be compared to the costs of each manufacturing step to point out the overlap of costs and sustainability. The last chapter closes with a summary and a discussion that contains recommendations for further research.

## **CHAPTER 2 – REVIEW OF LITERATURE**

For a better understanding of this research study, the following chapter gives a review of the current work regarding product life cycle and how it is related to sustainability and cost reduction. This also includes an overview of the most common techniques to reduce cost and increase sustainability. In addition, existing approaches, methods and software are presented within this chapter.

### **2.1. Basics of Sustainability**

Despite its increasingly widespread use, the term and concept of sustainability has remained ambiguous, vague, and non-binding in its consequences. However, sustainability is becoming an important aspect in politics, industry and everyday life. Should the use of the concept of sustainability be more than just a fashionable phrase, it requires not only rhetorical interpretations of existing practice, but also an in-depth discussion of the importance of this concept and its contents (Linne and Schwarz 2003).

#### **2.1.1. Background of Sustainability**

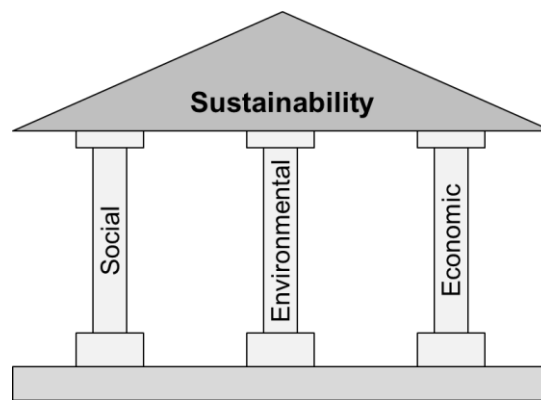
The general principle of sustainability greatly increased in popularity at the conference in Rio de Janeiro in 1992. However, it had many precursors. Since the early-1970s, there was a new debate on the "sustainability" of economic activity. Important events were the growth critical publication "Limits to Growth" in 1972, which took place in the same year as the first World Environment Conference which

was held in Stockholm and followed by the "Symposium on the economics of exhaustible resources" two years later. Based on these three milestones "sustainability" was first defined as the question of the optimal use of natural resources (Hauff 2014). The report of the "Brundtland Commission", published in 1987, used the term sustainable development to describe a new and comprehensive political model of the world community. The objectives of this model are the environmental protection and economic development that are connected with the demand to meet the needs of both today's and future generations (Hinrichsen 1989). After the Rio Conference, there was a variety of following conferences during which the vision of sustainable development was further concretized (Hauff 2014).

### **2.1.2. Sustainability and Sustainable Development**

The Brundtland Report is regarded as one of the most important contributions to the development and definition of the vision of sustainable development. However, there were a number of publications or opinions that have influenced this report. Of particular note is the first report on the Club of Rome. The report is based on a forecast which has the following central message: exponential growth leads to exceeding the natural limits of nature, whereby particularly a scarcity of exhaustible resources such as oil, occurs. This was an extreme contrast compared to the optimistic growth models of the capitalistic and dominant economic systems at that time. The forecast claims that up to the year 2100 crisis phenomena will occur such as a drop in the population, a de-industrialization and a massive restriction of the usual living conditions (United Nations 2011). Referring to the definition by Brundtland,

sustainable development is “development that meets the needs of the present without compromising the ability of future generations to meet their own needs” (United Nations 1987). The 3 pillars of sustainability have been identified as economic development, social development, and environmental protection, as renewed by the United Nations in their 2005 World Summit Outcome Resolution (United Nations 2005) (see Figure 3.). These components interact and affect each other in any real world application.



**Figure 3: The three dimensions of Sustainability**

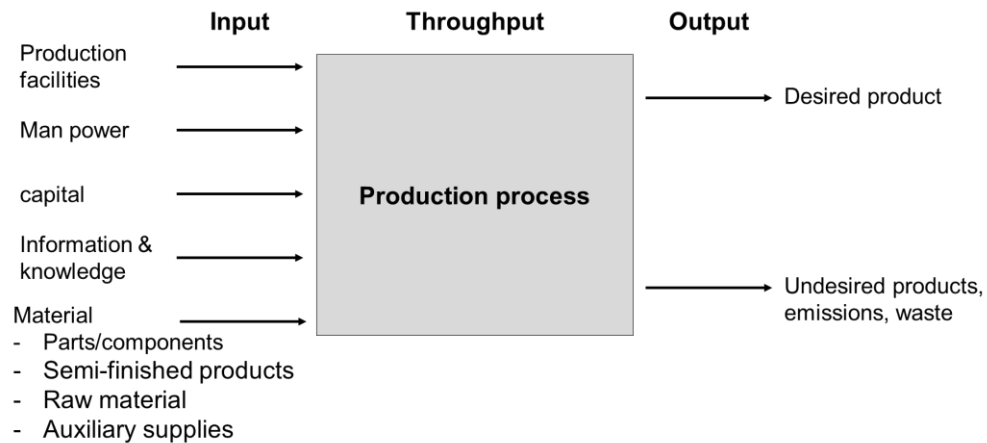
The three pillars must be considered simultaneously given their intricate interactions (Seliger 2007). In this study, the scope will be limited to sustainable manufacturing of products..

## **2.2.Product development and its influence on production**

According to Westkämper, production includes all technical and organizational processes for manufacturing, preserving and recycling of tangible and intangible assets through the product life cycle (Westkämper 2006). In addition to the initial stages of the life cycle such as: research, development, or design and manufacturing, this



definition also includes the phases of product life where customs utilize and ultimately recycle the product. On a process-level, production can be described as a transformation process, which consists of criteria related to output, input, and throughput (see Figure 4) (Dyckhoff and Spengler 2007).

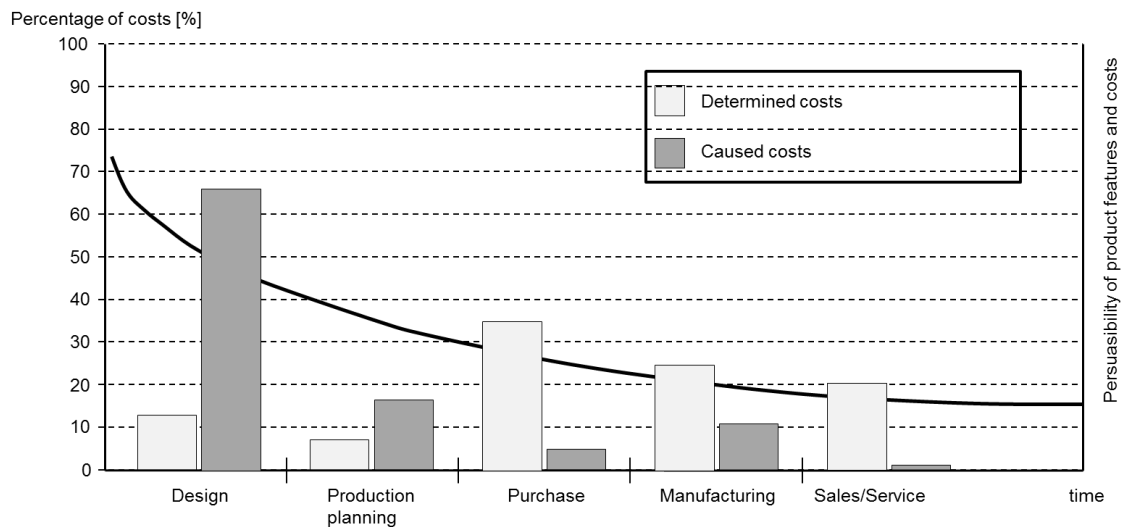


**Figure 4: Production systems as an Input-Throughput-Output process (Dyckhoff and Spengler 2007)**

In contrast, manufacturing only relates to the production of material goods, using resources such as: materials, energy, equipment, people, capital, information and knowledge (Westkämper 2006). Management of resources in combination with the individual manufacturing processes leads to the desired quantities and qualities of goods at scheduled times and targeted costs (Schenk et al. 2014). The factor time is of particular importance today because of changing market conditions and customer needs. Furthermore, a shorter production time often leads to decreased manufacturing cost. This can be achieved by shorter lead times, the reduction of production steps and through the use of new production technologies. Many production costs are determined in advance during the product development phase (Bullinger et al. 2008).

Therefore, even the use of the most efficient production techniques has a comparatively low potential for reducing the cost.

Figure 5 shows the relationship between the origin of costs and where the costs occur. The design phase is responsible for nearly 70 percent of the fixed costs and causes approximately ten percent of the costs incurred during the manufacturing process. In comparison, the production phase has a much lesser effect of about 10 percent on the fixed costs, while it determines up to 25 percent of the fixed cost. It becomes apparent that a substantial part of the costs are incurred in the production of a product, but are caused during the design of a product (see Figure 5). A production-oriented design can consequently help to reduce the manufacturing costs and thus reduce product unit costs significantly (Westkämper 2006).



**Figure 5: Assessment and cost responsibility within the production process (Westkämper 2006)**

In practice a production-optimized design can reduce the cost of the product by between 30 - 50 percent (Eversheim et al. 1995). In the following, different methods for efficient product development are presented.

### **2.2.1. Simultaneous Engineering**

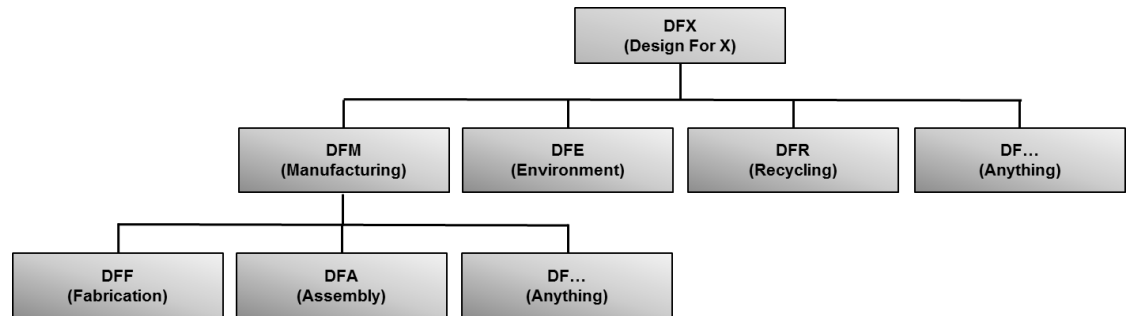
Simultaneous Engineering is a fundamental approach for product development during the design phase. In contrast to traditional product development, the formerly strictly sequential processes are performed in parallel or overlapping in time for simultaneous engineering. Hence, the duration of the entire development phase can be shortened. A highly effective working method for this approach can be found in multi-disciplinary and cross-divisional teams. Simultaneous Engineering, which is also known as concurrent engineering, can help identify problems earlier, which would otherwise not be discovered until later in the development chain or during the design of the production process (Gaubinger et al. 2014). The late discovery of problems often results in restrictions or high costs for troubleshooting (Eversheim et al. 1995).

For the successful implementation of Simultaneous Engineering the early exchange of information between the parallel operating processes is essential. Since it is often difficult to design a production process when the product design is not yet complete, and on the other hand, product design can only be fully optimized for production when the process is defined, both processes should be considered and evaluated in parallel. Methods have been developed to support the product continuously for manufacturability checks during product development (Bullinger and Warschat 1995).

### **2.2.2. Design for X**

The aim of production-oriented product design, is to design components so that the subsequent production cost is as low as possible (Eversheim et al. 1995). In

support of the product design there are a variety of methods that can be summarized under the term Design for X (DFX) as seen in Figure 6(Huang 1996).



**Figure 6: DFX- Methods (Huang 1996)**

Although all DFX methods have a different scope, the approaches follow a similar process for evaluating a product's design and relationships with the manufacturing process, measuring performance, and continuously improving (Huang 1996).

The Design for Manufacture and Assembly (DFMA) method of Boothroyd Dewhurst analyzes a product during the development process with manufacturing and assembly oriented design in mind. The method supports engineers in the evaluation of their product design and in identifying weaknesses regarding manufacturability. The result of this analysis can be used for the optimization of the product design. The DFMA method consists of two methods: Design for Manufacture and Design for Assembly (see Figure 7) (Boothroyd et al. 2011).

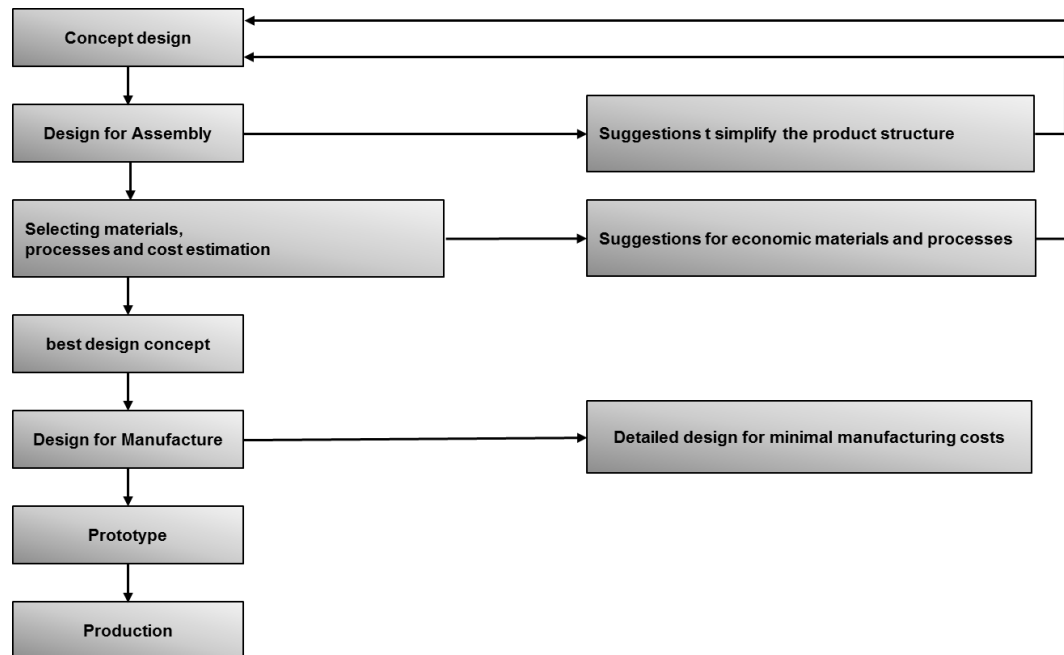


Figure 7: process steps of DFMA (Huang 1996)

### 2.2.3. Design for Assembly by Boothroyd- Dewhurst

The method Design for Assembly (DFA) was developed by Boothroyd and Dewhurst in 1977. The objective of DFA is to make sure that the product is easy to assemble and therefore aims to enhance the assimilability of the product by assisting in the selection of materials and assembly processes. The method focuses on the requirements of the assembly of the product. Therefore, the application of DFA methods systematically tries to reduce the number of components by integrating them into each other or changing the design of the components so that they can be adjusted, handled and installed easily. The first step is to assess all components by asking questions such as whether a part moves relative to other parts already assembled, whether parts must be made of different materials, or whether it is necessary for a part to be separate from all other parts already assembled (Boothroyd et al. 2011):

If all three questions are answered positive, the component is considered a critical component and must remain separate. All non-critical components can be omitted or integrated into one of the critical components. In the second step, the assembly time in terms of efficiency as well as the difficulty of the installation steps is analyzed. For this purpose, a separate DFA rating system is used, based on the Methods-Time Measurement system (MTM). MTM calculates the handling and assembly time of each component (Huang 1996), which are then summed to obtain the total estimated assembly time  $T_{EAT}$ . To evaluate the efficiency of the assembly, a reference value is used to compare the results to the minimal assembly time. This value is based on the assumption that only critical components are present in an optimized product and that every component can be mounted in three seconds. Finally, the design efficiency  $DE$  can be calculated as a function of the number of critical components is ( $n_{crit}$ ) and the actual total assembly time  $T_{EAT}$  (see EQ.1) (Huang 1996).

$$DE = \frac{3 * n_{crit}}{T_{EAT}} \quad (\text{EQ. 1})$$

The design efficiency can now be used as a key figure, in order to compare different product designs. A redesign, based on the aim to reduce the number of parts, can be analyzed by the DFA method and compared using the calculated design efficiency with the previous design. It should be kept in mind that the design efficiency metric, is not indicating an absolute value, and only takes into account how the DFA optimized design compared to its predecessors (Eskilander 2001).

#### **2.2.4. Design for Manufacturing**

After the adjustment of the product design, the next step is to analyze the manufacturing and associated costs of the individual components by applying DFM. Therefore a list of questions with examples for different manufacturing processes is included in DFM. These questions support engineers to specify and characterize the current design. Manufacturing-oriented design (DFM) includes product design activities that lead to minimization of production cost and time. One of the main principles of DFM is to reduce the complexity of the product and its manufacturing process, from which the following objectives of DFM can be derived (Boothroyd et al. 2011):

- Simplification of the manufacturing process
- Minimization the number of manufacturing processes per component
- Decrease of manufacturing steps through process integration

By changing the design of a product such as the shape, dimensions and materials the designer can affect the applicable manufacturing processes and machine tools. The processes that are available for manufacturing form the constraints for the design engineers. For each of the various manufacturing processes, on the other hand, there exists a particular design guideline to ensure easier processing (Ponn and Lindemann 2008). It helps to take manufacturability into account in the early stages of the product development process, so that products can be produced with less effort and with the lowest possible manufacturing costs and cycle times.

### **2.2.5. Design for Environment**

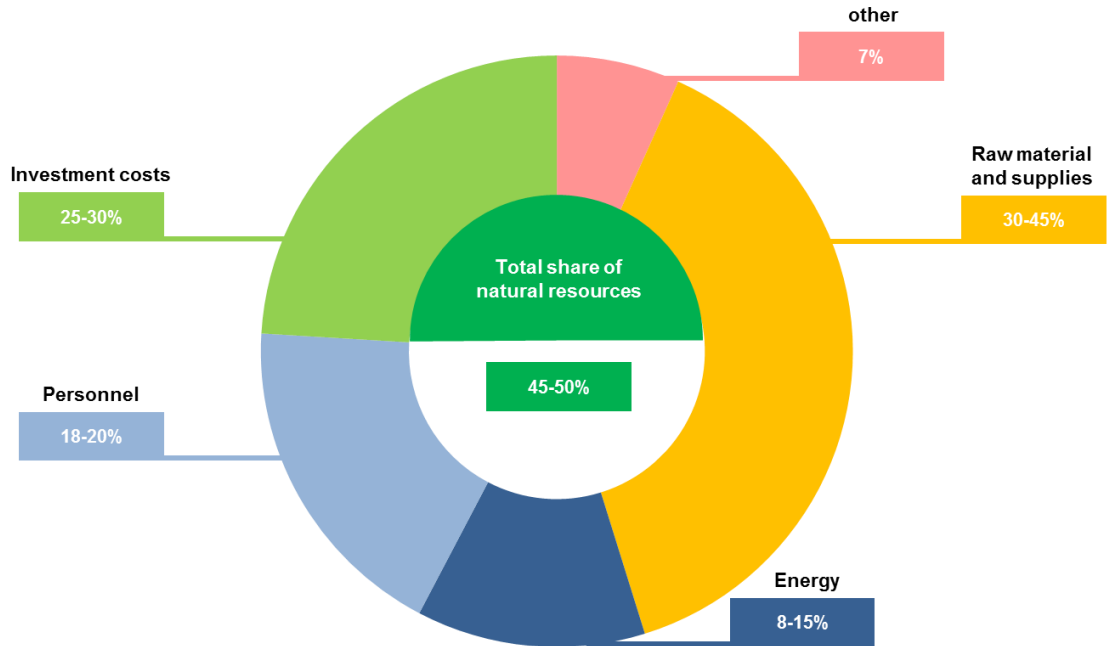
Design for Environment (DfE) was originally designed to provide design engineers with a set of guidelines that should be taken into consideration during the product development process (Rose 2001). With the increasing public interest in sustainably produced products and the increasing relevance for company's competitiveness, DfE has become an integral part of the product development process for many companies today (Huang 1996).

DfE takes all phases of the product life cycle into account. According to ISO 14040, the term "product life cycle" is the sum of all phases from the acquisition of the raw material to recycling and disposal at the end of the products life. The term product can be used as a synonym for all goods and services (ISO 14040:2006). Through the comprehensive approach of DfE there exist a large number of factors that have to be considered during sustainable production, as described in the following sections.

### **2.3. Cost and environmental impact factors during manufacturing**

In the context of the potential depletion of abiotic resources and rising raw material costs, material-efficient production is gaining greater importance. Today, raw material and energy costs sum up to over 50% of the total cost of a product, representing one of the largest contributing factors. Optimizing the use of resources and energy is essential for a sustainable green growth of a company and being competitive at the same time (see Figure 8) (Europe INNOVA 2012).

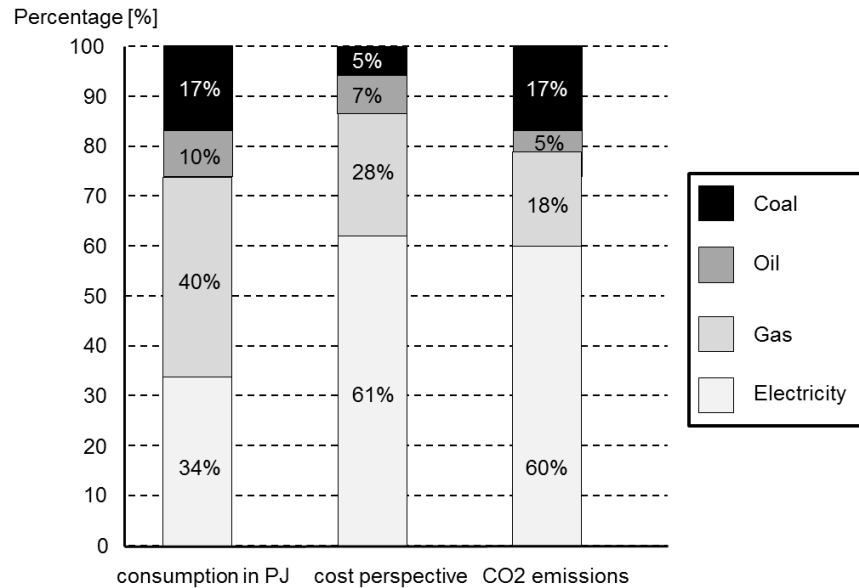




**Figure 8: Structure of the total costs in manufacturing (Europe INNOVA 2012)**

### **2.3.1. Energy**

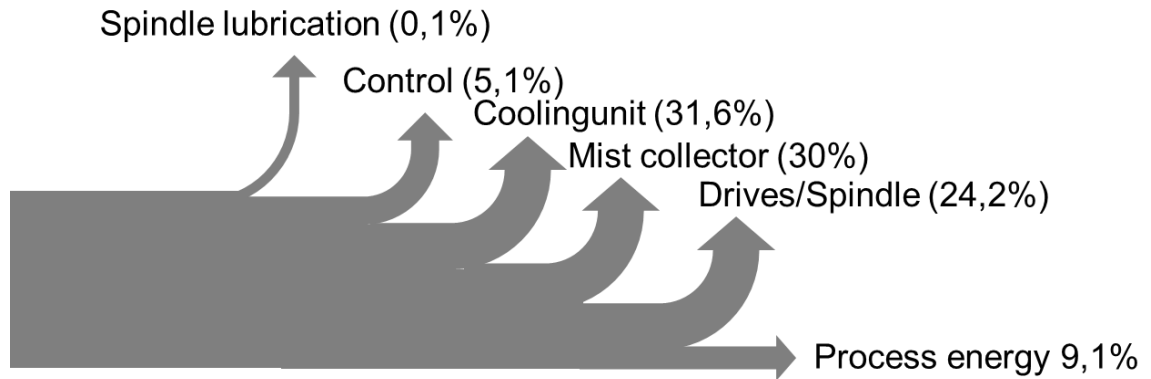
According to a survey conducted by the KfW-Group, more than 60% of all responding companies have already started to implement energy efficiency (Thamling et al. 2010). According to this survey, the German industry is responsible for 46% of the national energy consumption and 35% of the national gas consumption. Therefore, companies directly and indirectly take a share of the responsibility for the negative environmental effects of conducting business. From a cost perspective, energy-efficient production is of high relevance, as energy prices for electricity, gas and oil have increased disproportionately in recent years. This leads to energy costs, which can equal up to 20% of the total cost of a product (Apostolos 2013).



**Figure 9: Comparison of the energy consumption of the German manufacturing industry (Thiede 2012)**

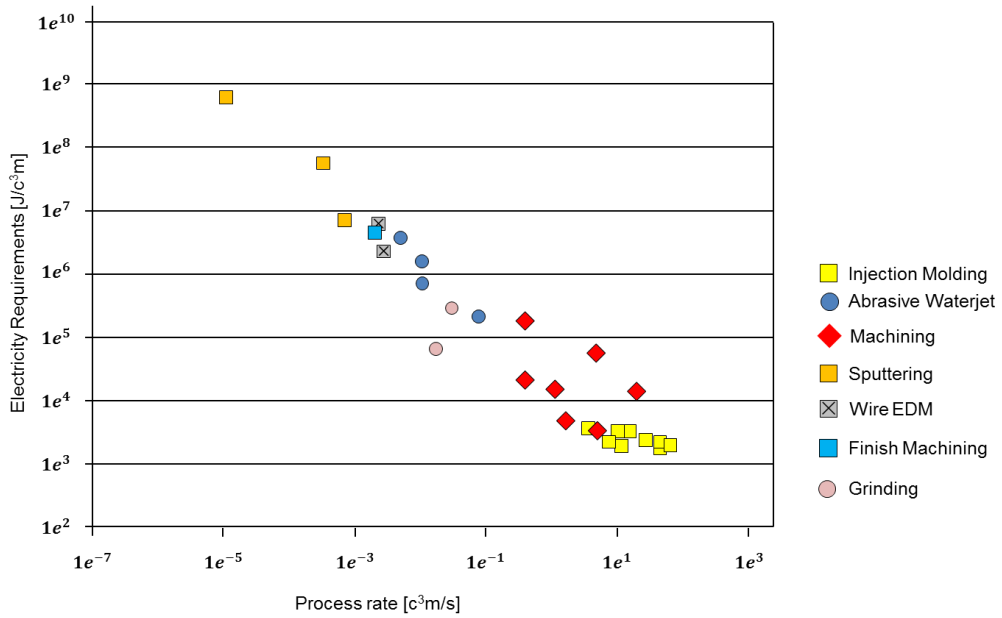
On a process level, heating and process heat from gas, coal and oil represent approximately 75% of total energy consumption. However, a large part of the costs and CO2 emission in German manufacturing companies are caused by electrical energy (see Figure 9).

Electrical energy is used in manufacturing companies to produce mechanical energy to run pumps, air conditioners, air compressors and the actual production machines. Production machines especially need different amounts of energy, depending on the process and state. Modern production machines combine a variety of different functions, e.g. cooling, lubrication, chip removal and tool change. The actual main function, the machining of the work piece is only one of many energy consumers (see Figure 10) (Thiede 2012).



**Figure 10: Sankey diagram for energy consumption of a chip removal process (Thiede 2012)**

These additional functions are often responsible for a large part of the total energy consumption. Most production machines require a lot of energy to start and to stay ready-to-operate. From this standby condition only a relatively small amount of energy is needed to process a work piece. The required energy for the actual machining depends on the material used and the settings such as feeding rate (Gutowski et al. 2006).



**Figure 11: Specific energy consumption for different manufacturing processes (Gutowski et al. 2006)**

Figure 11, shows that across a range of manufacturing processes, the energy requirement increases with decreasing processing rate. Therefore, a strategy for energy-efficient production is to increase the processing rate of the production process in order to save energy. Figure 11, also shows that certain manufacturing processes, at the same processing rate, consume less energy than others. Hence, changing the manufacturing process can save energy costs (Gutowski et al. 2006).

### 2.3.2. Resources

Another aspect of sustainable production is resource efficiency. Production processes transform raw materials and other inputs into finished products, while the ratio of input used for production output is described as resource efficiency. (Europe INNOVA 2012).

Increasing resource efficiency leads automatically to a reduction of materials demand and also lowers the requirement for production of new material. By reducing the production of new material, the extraction of natural resources, energy demand, emissions and other threats to the environment can be decreased (Allwood et al. 2013). The four materials which have the most harmful emissions are steel, plastic, paper and aluminum, which are the basis for almost every modern product (Allwood et al. 2010). Improving resource efficiency can often be achieved by relatively small changes in the manufacturing process, such as reduction of cuttings and rejects or improved recycling of production wastes (Europe INNOVA 2012).

### **2.3.3. Consumables**

The main consumables used in most machining processes during operating time are: cuttings tools, cutting fluid and lubricant oil.

#### **Cutting tools**

Cutting tools and inserts wear out during machine operations and must be replaced. Otherwise they can cause increasing energy demand and a decrease of production quality. In the worst case it causes damage to the product or to the machine itself. Often tools can also be regraded and used again. While cutting tools compared to other consumables are relatively expensive, they are often amortized over various products manufactured (Dahmus and Gutowski 2004).

#### **Cutting fluids and lubricant oil**

During manufacturing, especially machining, cutting fluid and lubricant oil are one of the main sources of environmental impact. In order to pursue sustainable

manufacturing of products, it is an important step to reduce the usage of these fluids or to use environmental friendly alternatives (Tan et al. 2002). However, cutting fluids are often necessary to ensure the quality of manufacturing processes, since they improve the cutting performance with cooling and/or lubrication effects. For low cutting speeds, lubrication is more critical whereas the cooling effect becomes more important at higher cutting speeds due to more heat production. A large variety of different types of cutting fluids are available. To classify them, different standards can be used (Grzesik 2008). A common norm is the German DIN 51385 that divides cutting fluids into non-water miscible fluids, straight or neat oils which all are supplied as premixed products. Water miscible products, on the other hand, are often supplied as concentrates and must be diluted before application (DIN 51385:2013-12). Cutting fluids can also be categorized into the following four categories (Boothroyd and Knight 2006):

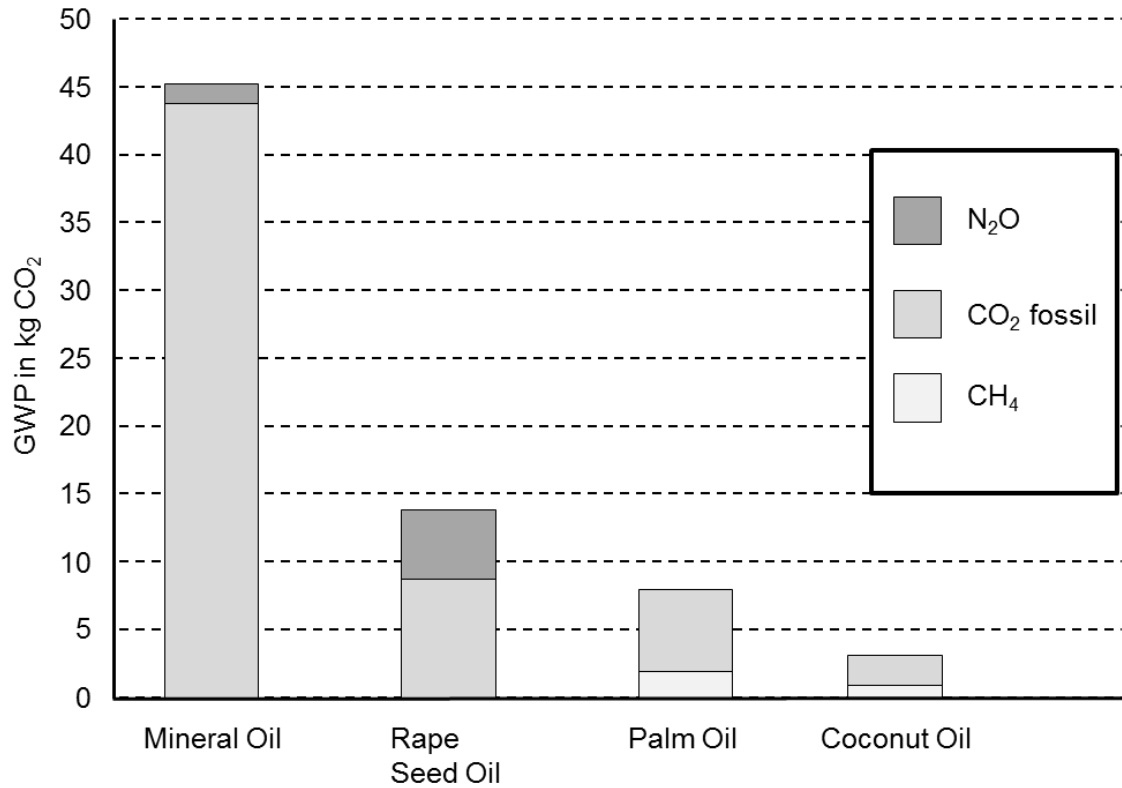
- Straight or neat oil
- Mineral-soluble oils
- Semi-synthetic fluids
- Synthetic fluids (mineral oil free)

According to a survey conducted by the US manufacturing industry, around 80% of cutting fluids used are water-based emulsions of oil or synthetic fluids (Grzesik 2008). Cutting fluid is used in almost every industry to enable high speed, high efficiency, high accuracy and long tool life. However, there are also significant costs associated with cutting fluids for purchase, maintenance and disposal (Stephenson and Agapiou 2006). To keep the performance on a constant level and prolong its work life,

cutting fluids have to be maintained properly by testing pH-levels and determining the oil concentration values regularly, since part of the fluid vaporizes during the use phase and are released into the atmosphere. Cutting fluids are related to significant environmental and health impacts such as dermal initiation, air, water and soil contamination. Therefore, there are strict national recommendations of permissible levels (Boothroyd and Knight 2006).

### **Vegetable based cutting fluids**

Besides the mineral oil-based cutting fluid, recent studies investigate the utilization of vegetable oil-based metalworking fluids including successful applications for machining. Ferrous metals, revealing the possibility of an environmentally friendly option with similar performances (Lawal et al. 2012). Vegetable based cutting fluids contain fatty acids extracted from a variety of vegetables such as: soy beans, sunflowers, rapeseed, olives or coconut (Shashidhara and Jayaram 2010). According to Alves and Oliveira, it was found that those vegetable oils contribute over ten times less CO<sub>2</sub> than mineral oil based cutting fluids. Per kg of mineral oil an equivalent of 50kg CO<sub>2</sub> is released which can be compared to coconut oil which only contributes about 6kg of CO<sub>2</sub> equivalent emissions (see Figure 12) (Alves and Oliveira 2006).



**Figure 12: Global Warming Potential (GWP) per kg of cutting fluid (Alves and Oliveira 2006)**

Besides the low CO<sub>2</sub> emissions, vegetable oil based cutting fluids are also highly bio degradable, cheaper and highly viscous. On the downside, vegetable oil based cutting fluids have a low corrosion protection and low thermal stability. A complete list of advantages and disadvantages can be seen in Table 1 (Lawal et al. 2012).



**Table 1: Advantages and disadvantages of vegetable oil as lubricants (Lawal et al. 2012)**

<b>Advantages</b>	<b>Disadvantages</b>
<ul style="list-style-type: none"><li>▪ High biodegradability</li><li>▪ Low pollution of the environment</li><li>▪ Compatibility with additives</li><li>▪ Low production cost</li><li>▪ Wide production possibilities</li><li>▪ Low toxicity</li><li>▪ High flash points</li><li>▪ Low volatility</li><li>▪ High viscosity indices</li></ul>	<ul style="list-style-type: none"><li>▪ Low thermal stability</li><li>▪ Oxidative stability</li><li>▪ High freezing points</li><li>▪ Poor corrosion protection</li></ul>

## **2.4.Measuring environmental impact**

In order to identify sustainable manufacturing processes, their environmental impact has to be measured. In the following subchapters, indicators for sustainability and tools are explained.

### **2.4.1. Life Cycle Assessment**

Life Cycle Assessment (LCA) is a science-based analysis of the environmental impacts of product systems. During its early attempts around 1970 to 1990, no standardized version of LCA existed, which made the findings from such analysis hard to comparable. Since 2000 the first series of LCA standards were published. These standards are called ISO 14040 and 14044 (Klöpffer and Grahl 2014). According to those standards, LCA has been defined as follows (ISO 14040:2006):

“LCA studies the environmental aspects and potential impacts throughout a product’s life from raw material acquisition through production, use and disposal. The general categories of environmental impacts needing consideration include resource use, human health and ecological consequences.”

This definition excludes the pillars of society and economy and focuses on the ecological influence of production systems. Since the first standards were established, the method was criticized as being too complex regarding the demanding set of requirements which led to a trend of simplifying LCA to make it more flexible and easier to use (Hesselbach and Herrmann 2011).

Those simplifications of LCA are represented by simplified/streamlined Life Cycle Assessment (SLCA) which can be used as a first step of a full LCA or even as a stand-alone study. However, SLCA is not recommended for use in official publications but can be sufficient for internal assessments (Klöpffer 2012).

### **General structure of LCA**

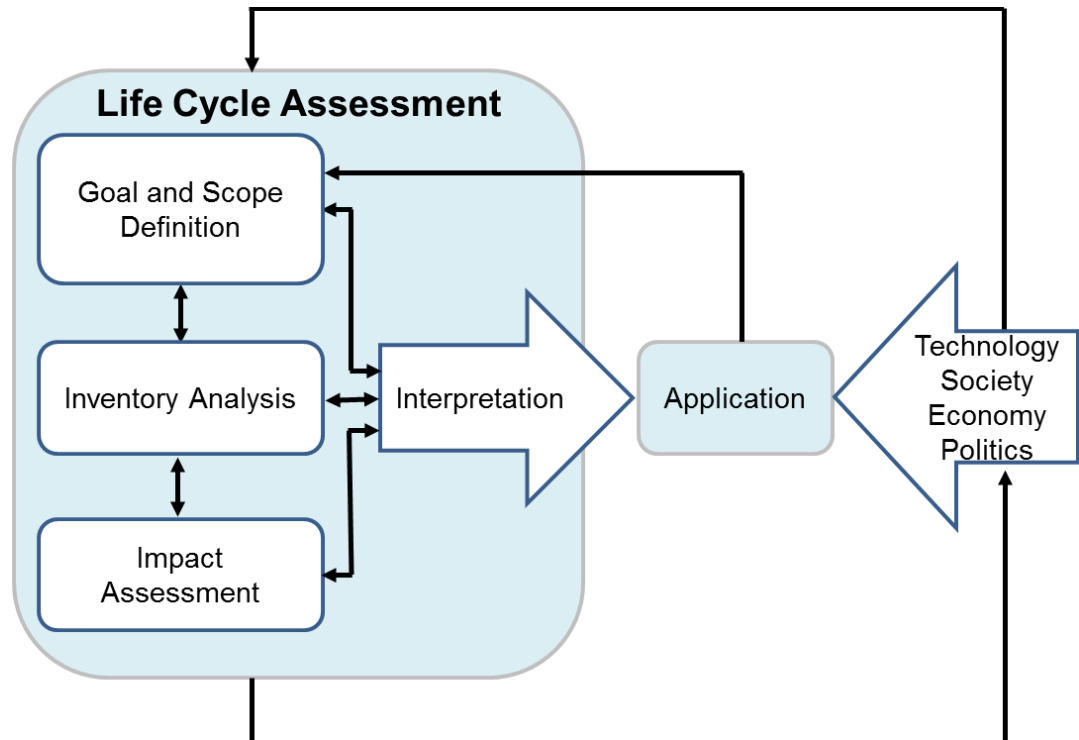
A life cycle assessment includes the compilation of all significant input and output flows and an assessment of the potential environmental impacts of a product. For this purpose, the entire life cycle beginning with the supply of raw materials, production, use, and disposal or recycling of the product, has to be taken into account. Every phase is analyzed for its environmental impact by energy and material use. Conducting a LCA is usually divided into the following four steps (see Figure 13) (ISO 14040:2006):

1. Goal and scope definition
2. Inventory analysis

3. Impact assessment

4. Interpretation

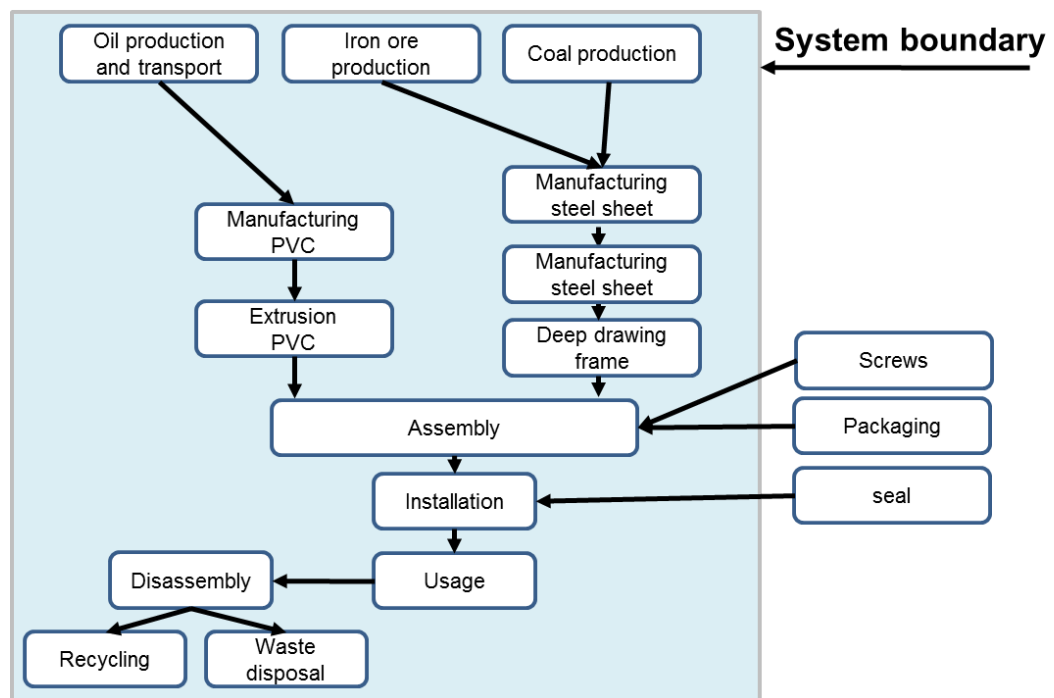
These steps are iterative. When the results are planned to be published, an independent committee has to conduct a critical review first (Guinée 2006).



**Figure 13: General steps of Life Cycle Assessment (Jensen et al. 2006)**

The first step in the goal and scope definition phase is to define and explain the objectives of the study including its intended application and the audience. The scope definition issues the main characteristics such as the temporal, geographical and technology coverage of the LCA study and determines the functional unit that will be analyzed (Herrmann 2010).

For example, environmental impacts of a train cannot easily be compared with impacts of a car. A suitable functional unit is 'driving 100 kilometers in 1 hour with 1 person'. Another example is the functional unit of paint. It is necessary to compare the function 'covering 10 square meters of a wall without wallpaper' instead of '1 liter of paint' because the paints might have different mileage. The functional unit is often drawn as a diagram of the unit's processes, which clarifies the system boundaries and the interdependence within the production system. An example is given in Figure 14.



**Figure 14: Simplified example of a PVC window system boundary (Klöpffer and Grahl 2014)**

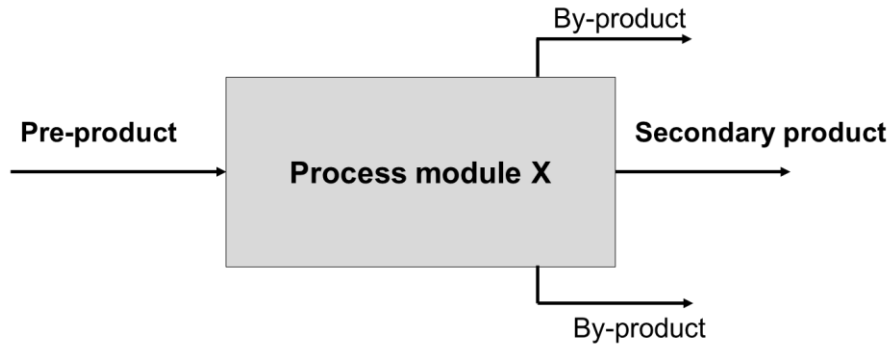
A particular problem is the omission of whole life cycle stages when products with different production processes are compared since it may cause asymmetry of the systems. Depending on the production process the major environmental impact of a product might happen at a different life cycle stage which lets a product appear to be

more sustainable when this stage is not included in the assessment. Therefore, it has to be verified that an omission does not influence the symmetry of the systems. Whenever the goal of the LCA is to compare different products, it is common to exclude life cycle stages that are identical (Klöpffer and Grahl 2014).

The first step of the LCA also includes the problem of availability and quality of data needed to perform a comprehensive analysis. It has to be decided for which processes require collection of primary data or whether existing data can be used and the level of detail for the study. In this context the approach of simplified LCAs is often discussed, since they require less data and are therefore less time intensive and easier to conduct (Christiansen 1997).

### **Inventory Analysis**

The inventory analysis is the result of material flow or mass flux analysis. It includes the collection of data and the calculation method for quantifying relevant input and output flows of a product system within the specified scope definition. The inventory analysis serves as a basis for impact assessment and should be performed transparent and on a uniform level of detail for each process (Klöpffer 2012). To visualize the production process flow charts can be used. Flow charts of production processes often have different branches for byproducts or waste which should be also taken into account to preserve the symmetry of the system (see Figure 15) (Eversheim 2013).



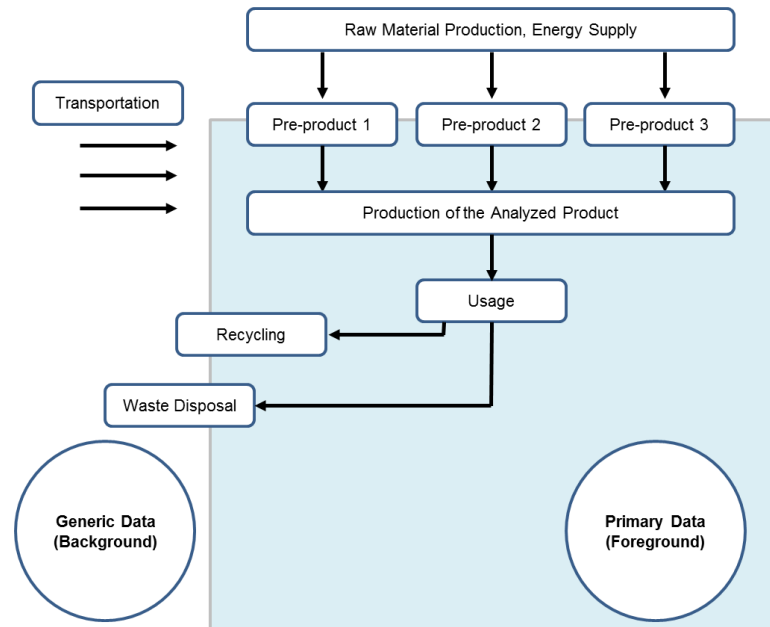
**Figure 15: Flow chart to visualize production process (Eversheim 2013)**

The energy analysis of the production process is in addition to the analysis of the material flow, and is an important part of the inventory analysis. It is not the amount of energy that can be purchased in the form of electricity, heat or fuel to that has to be taken into account, but more importantly, the determination of the primary energy that is expended to provide this final energy, which depends on the efficiency of the energy conversion process in the power plant.

If the production data for the energy demand is not available, the minimum final energy demand can be calculated from material values. However, this is usually not the most accurate approach. Due to losses in the processes, the real energy demand will be much higher (Klöpffer 2012).

Gathering process specific data for the inputs and outputs is the most important task of the inventory analysis. An accurate analysis of the manufacturing processes of the product, including its corresponding raw materials, is the basis for this. Furthermore, an analysis of transport processes and waste streams within the selected geographical and temporal system boundary should be conducted. For tangible products the Bill of Material (BOM) indicates what materials and quantities e.g. per piece or mass, are used. The data must be gathered with this reference, so that they

later can be converted easily on the reference flow according to the functional unit. When there are datasets as generic data from a reliable database for materials that are contained in the product, this data can be used alternatively (Simonen 2014).



**Figure 16: Schematic data collection (Klöpffer and Grahl 2014)**

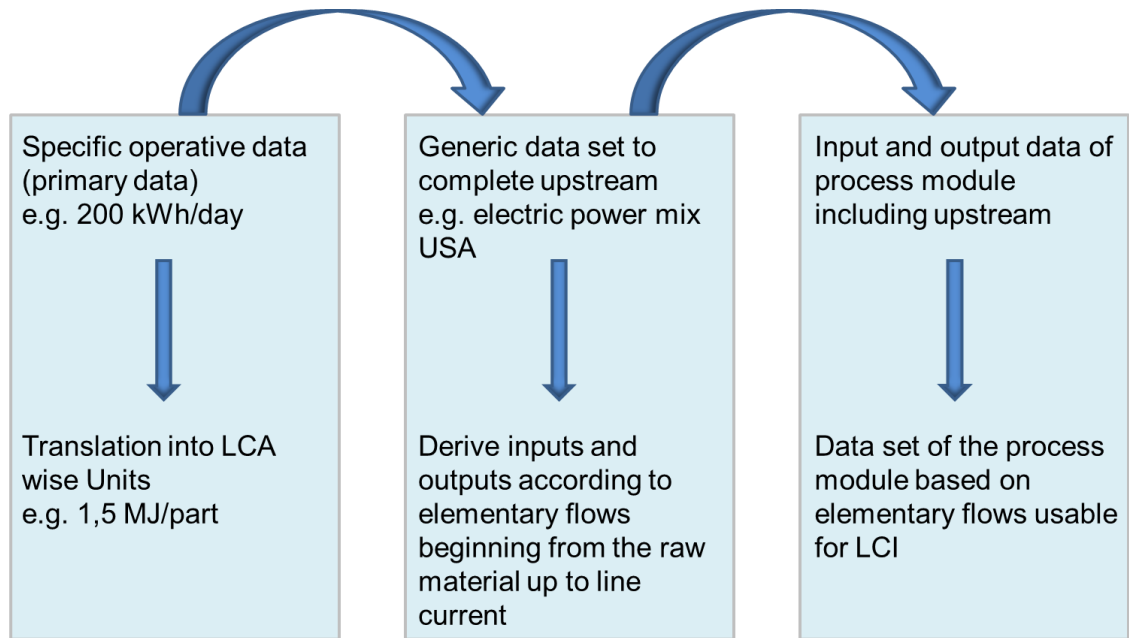
Since it is hardly possible that all data can be gathered as primary data for a specific product, almost every inventory analysis consists of primary, generic data and estimated data. The extent to which primary data is available or can be collected depends significantly on whether and how involved the manufacturers of the respective products are in the life cycle assessment (see Figure 16). If the manufacturer itself conducts or orders the LCA, the expected data quality will be very high. Specific records usually allow a better spatial and temporal allocation of emissions and resource consumption (Klöpffer and Grahl 2014). Some specific data can be relatively easy to collect at the manufacturer while other data can be more difficult to collect (see Table 2).

**Table 2: Collectability of specific data (Jensen et al. 2006)**

<b>Easy collectable</b>	<b>Harder collectable</b>
<ul style="list-style-type: none"><li>▪ Use of materials</li></ul>	<ul style="list-style-type: none"><li>▪ Emission to air</li></ul>
<ul style="list-style-type: none"><li>▪ Energy and different energy forms e.g. heat (without upstream chain)</li></ul>	<ul style="list-style-type: none"><li>▪ Emissions to water</li></ul>
<ul style="list-style-type: none"><li>▪ By-products</li></ul>	<ul style="list-style-type: none"><li>▪ Contamination of soil and groundwater</li></ul>
<ul style="list-style-type: none"><li>▪ Production waste</li></ul>	<ul style="list-style-type: none"><li>▪ Information on ionizing radiation, biological and emissions</li></ul>
<ul style="list-style-type: none"><li>▪ Operating and auxiliary materials</li></ul>	<ul style="list-style-type: none"><li>▪ Nusances (noise, odor)</li></ul>
<ul style="list-style-type: none"><li>▪ shipments</li></ul>	

Especially for different types of energy supplies, transportation, common materials and chemicals the use of generic data is often necessary. Generic data can be useful in LCA even if specific data is available but has unverifiable quality. Therefore the generic data should not be seen as a bias of the life cycle assessment, but can still be a very valuable source of data (Hendrickson et al. 2006). As shown in Figure 17 a combination of generic and collected specific data can be used to generate a qualitative data set for the analyzed process module (Klöppfer 2012).





**Figure 17: Translation of operative data to process module based data set (Klöpffer 2012)**

After all considerable process modules are defined and the input and output data is gathered, the last step of the inventory analysis is to link the process modules. Existing software tools such as GaBi, Umberto and Ecoinvent can help to link the different modules properly.

### **Life cycle impact assessment**

The life cycle impact assessment (LCIA) analyzes the inventory analysis data in terms of their impact for the environment and categorizes the data accordingly. This process follows several mandatory steps according to DIN EN ISO 14040:

Selection of impact categories, category indicators and characterization models

Assignment of LCI results (classification)

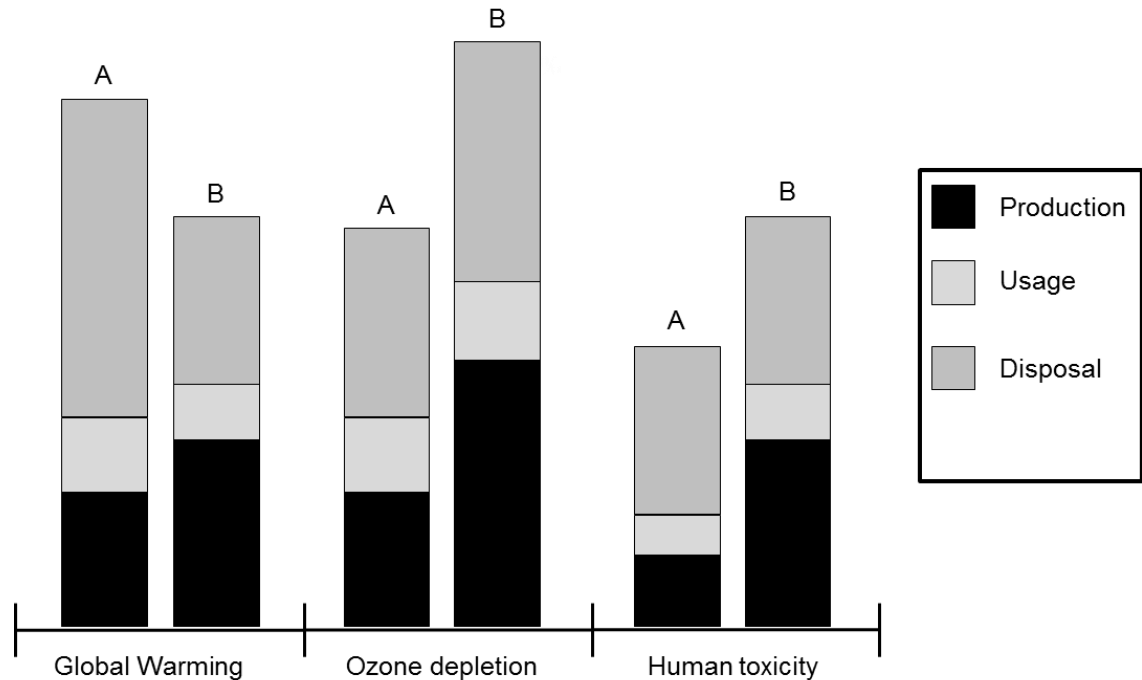
Calculation of category indicator results (characterization)

- Category indicator results (LCIA results, LCIA profile)

During the classification, the data is assigned to the impact categories. Every other material which accounts for this category is converted by fixed factors into equivalents of that indicator. For example, nitrous oxide is multiplied by 25 to receive a CO<sub>2</sub> equivalent. All equivalents are summed to reach a final result for the impact category. In some cases, a parameter can be assigned to several impact categories e.g. Methane (CH<sub>4</sub>) emissions. Methane contributes to both the Global warming potential (GWP) as well as to summer smog. In addition to the direct effects, indirect effects are determined such as human health hazard by environmental damage (ISO 14040:2006).

In the following step, the characterization of the environmental impact, the results are quantified. There are two assessment approaches. The first is the midpoint approach which includes direct impact categories like the change of tropospheric ozone concentration under the name ozone depletion. In contrast to that, the endpoint approach describes concrete damage categories. For example, the endpoint indicator of ozone depletion is loss of life years. On the one hand, since the knowledge of ozone depletion is getting more uncertain in the determination of the exact consequences on human health, the midpoint approach includes more facts and fewer assumptions. On the other hand, the endpoint approach is more demonstrative in presenting concrete effects instead of reference indicators only (Curran 2012).

By the use of weighting factors, the relative contribution of each parameter to each category is determined. As the last step, the results are summed and divided into the different life-cycle-stages. A common way to display the results is the eco-profile (see Figure 18).



**Figure 18: Example of an eco-profile (Herrmann 2010)**

The eco-profile has its advantages in the simplicity of illustration. In addition, advantages and weaknesses of the system become easily comparable and can be interpreted (Herrmann 2010).

### **Interpretation**

The life cycle interpretation is the last phase of the LCA process. Life cycle interpretation is a technique to identify, quantify, check and evaluate the results. According to ISO standards results, conclusions and limitations based on the findings of the previous phases have to be reported in a transparent manner. Part of the interpretation should be:

- completeness check – Ensure the completeness of the assessment
- sensitivity check – Assessing the sensitivity of the data elements that have the biggest influence on the results

- consistency check – evaluate the consistency of the analysis including system boundaries, data collection and impact categories for each alternative

These steps ensure that the LCA was conducted correctly according to ISO standards and that the results are not biased. The results can provide information that can be used by decision-makers to get a better understanding of the environmental and health impacts associated with each alternative. This information includes the environmental pros and cons of each alternative, but it does not include any information about technical feasibility, cost or social acceptance (Klöpffer and Grahl 2014).

### **Simplified LCA**

A major problem of LCA is the required time and cost to perform this study. In addition, data availability is often critical and therefore one of the most important criteria for the decision regarding whether a full LCA can be conducted or not. Alternatives to the full LCA are the Simplified (Streamlined) or Screening LCA, which are less complex and require less detailed data sets. Both versions, which in practice often are not clearly separated, work primarily with easily available or estimated data and also allow for the omission of life cycle phases. Although the results can be less accurate, both versions can be useful whenever a fast and simple analysis is sufficient. This is often the case when LCA is needed to enhance decision-making within internal processes or when different processes are compared. Especially for decision-making during the design phase, where only very little time is available, these methods have earned their right to exist. There are different approaches to simplify the LCA which occur at two levels (Jensen et al. 2006):

- What to do – Omission of parts of the full LCA

- How to do it – Simplifying procedures of the full LCA

Generally, approaches to simplify LCA aim to reduce the scope of process data or to eliminate life cycle stages. Another approach is to simplify the modeling procedures which results in a smaller amount of data that is needed for the assessment of processes. A study by Franklin Associates and RTI was done to compare the different approaches for streamlining LCA (see Table 3) (Todd and Curran 2007).

**Table 3: Overview of different Streamlining approaches (Todd and Curran 2007)**

Streamlining approach	Application procedure
Removing upstream components	All processes prior to final material manufacture are excluded. Includes fabrication into finished product, consumer use, and post-consumer waste management.
Partially removing upstream components	All processes prior to final material manufacture are excluded, with the exception of the preceding final material manufacture. Includes raw materials extraction.
Removing downstream components	All processes after final material manufacture are excluded.
Removing up- and downstream components	Only primary material manufacture is included, as well as any precombustion processes used in manufacturing. Sometimes referred to as a "gate-to-gate" analysis.
Using specific entries to represent impacts	Selected entries are used to approximate results in each of 24 impact categories, based on mass and subjective decisions.; other entries within each category are excluded.
Using specific entries to represent LCI	Selected-entries from the individual processes comprising the LCI that correlate highly with full LCI results are searched for; other entries are excluded.
Using "knockout criteria"	Criteria are established that, if encountered during the study, can result in an immediate decision.
Using qualitative or less accurate data	Only dominant values within each of 6 process groups are used. Other values are excluded, as are areas where data can be qualitative, or otherwise high uncertainty.
Using surrogate process data	Selected processes are replaced with apparently similar processes based on physical chemical, or functional similarity to the datasets being replaced.
Limiting raw materials	Raw materials comprising less than 10% by mass of the LCI total are excluded.

This comparison showed that none of the streamlining methods produced results that were identical to the full LCA. However, streamlined LCA can be successful when they include the dominant processes of the life-cycle of the product. In applications when the equivalent of a full LCI is not required, this becomes less important. To indicate areas in which simplifying is appropriate, a systematic analysis

based upon detailed knowledge of the production systems should be done. Nonetheless, it should be noted that streamlining LCA will always include the risk of obtaining a result that differs from the full LCA. Depending on the goal of each LCA, this risk might be acceptable. Table 4 shows where simplified and full LCA are frequently used (Jensen et al. 2006).

**Table 4: LCA applications. Bold “X” indicates the most frequently used (Jensen et al. 2006)**

Application	Level of detail in LCA	
	Simplified	Detailed
Design for Environment	X	
Product development	<b>X</b>	X
Product improvement	X	
Organization marketing	<b>X</b>	X
Strategic planning	<b>X</b>	
Choice between packaging systems		<b>X</b>

No matter which type of LCA is chosen, there are supportive software tools available.

#### 2.4.2. LCA Software

Especially detailed Life Cycle Assessment of product systems can be very complex. Therefore, LCA software tools can be very helpful. Generally, they include an extensive database of different materials and manufacturing processes which allows the user to use generic data whenever measuring specific data is exceedingly difficult. The first life cycle assessments were manually modeled and calculated. To improve these processes, spreadsheets were created. The first special program to create an LCA was a database extension for a spreadsheet program, which was published in 1985.

With the increasing amount of data, extensive product life cycles and policy requirements for reporting environmental impacts of product systems, the need for further specific and user-friendly software solutions became more necessary. While the first approaches were project-based or in-house developments, today there are a lot more software solutions available on the market (Luedemann and Feig 2014).

### **2.4.3. Value Stream Mapping**

Value Stream Mapping (VSM) is a method that helps to understand and draw the flow of material and information as a product makes its way through the value stream. Therefore, every value-added and non-value-added action within the production flow from raw material until the shipping process is taken into account. The focus of the VSM is on cost reduction through eliminating non-value-added activities and unnecessary wait times via applying a management philosophy which focuses on identifying and eliminating waste from each step in the production chain respective of time, motion and resources alike throughout a product's value stream, known as lean (Rother and Shook 2003).

However, the VSM does not provide any information about the process energy consumption or consumables. As a consequence, it does not give any conclusion of how much of each of those actually serve the value adding process steps. The primary shortcoming of traditional VSM is the lack of metrics to assess environmental and societal aspects of sustainability performance. In an effort to build upon and improve traditional VSM to capture additional sustainability aspects of the product flow and make this method more useful for identifying the environmental impact of a value

stream, different approaches were made (Brown et al. 2014). The EPA developed two toolkits: a lean and environmental toolkit and a lean energy toolkit. The first tool seeks to reduce the environmental waste such as pollutants and any hazardous materials used in production, while the other tool focuses on monitoring the energy consumption within the manufacturing system. Both tools collect data for each process and evaluate the environmental impact, allowing improvements to be targeted to necessary areas. The toolkits also mention how to add an EHS (Environmental, Health, and Safety) stamp to identify manufacturing processes with EHS opportunities (EPA 2007).

Based on the ideas of EPA, Faulkner et al (2012) developed Sustainable VSM (Sus-VSM), a tool that determines the sustainability of a process by using a comprehensive set of different metrics such as: process water, raw material usage, energy consumption, and social impact.

Water, oils, and coolants are used in various manufacturing operations and often large quantities are needed which have a large potential for environmental improvement. The fluids are tracked by the amount needed, used, and lost in each of the process steps. This is visualized by a three-box system below each process cell (see Figure 19) (Faulkner and Badurdeen 2014).

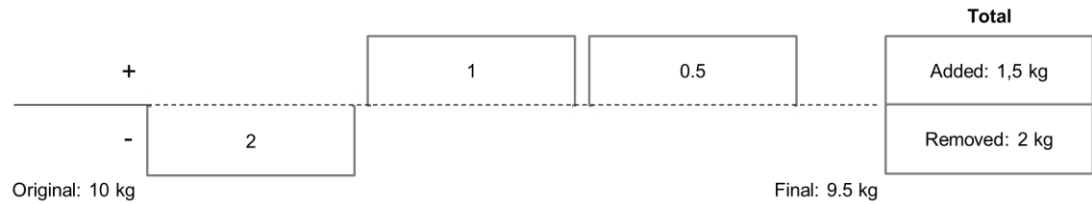
Process I			Process II			Process III			Total		
Needed	Used	Lost	Needed	Used	Lost	Needed	Used	Lost	Needed	Used	Lost
11	11	11	31	31	01	101	121	51	141	161	61

**Figure 19: Visual Representation of Process Water on Sus-VSM (Faulkner et al. 2012)**

The raw material usage metric displays the amount of material removed or added for a given process. An amount of material used is connected directly to the amount of

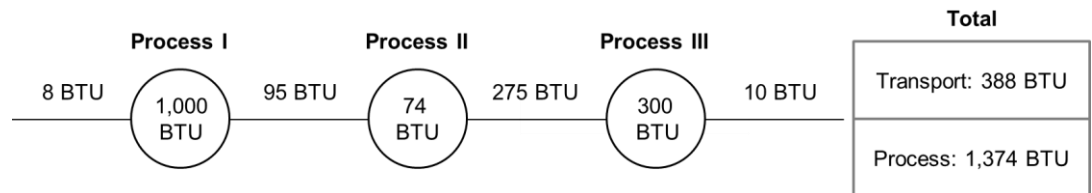


processing time that is needed to create a product and to energy consumption of the process. To visualize this, the Sus-VSM records the raw material metric by utilizing a dotted-line for the initial mass while the material added and removed during the process is recorded above and below the dotted-line, respectively (see Figure 20) (Brown et al. 2014).



**Figure 20: Visual Representation of Raw Material Usage on Sus-VSM (Brown et al. 2014)**

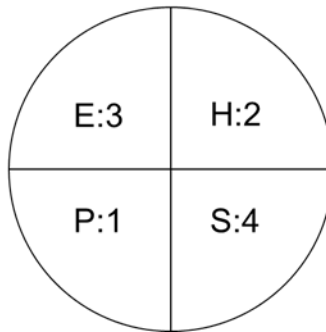
Another metric of Sus-VSM is energy consumption that identifies the amount of energy consumed by a process, but not the energy losses of the machines due to heat or inefficiencies. Based on the energy consumption data, Sus-VSM act as a map to identify which processes have high energy consumption and therefore should be further investigated to analyze inefficiencies. The energy consumed by each process is displayed as circles while the transportation is shown on the line between the circles, as seen in Figure 21 It is important to choose a common unit that is easy to convert e.g. BTU (Faulkner and Badurdeen 2014).



**Figure 21: Visual Representation of Energy Consumption on Sus-VSM (Faulkner and Badurdeen 2014)**

The social impact of a process can be divided into Physical Work and Work Environment. The Physical Work measure include the Physical Load Index (PLI) which is using a questionnaire to assess different body positions and the handling of materials and products. The Work Environment metrics categorizes risks into four different categories: Electrical Systems (E), Hazardous Chemicals/ Materials Used (H), Pressurized Systems (P), and High-Speed components (S). Those potential risks are then rated from 1-5, as seen in Figure 22, based on the likelihood and impact of such risk (Faulkner et al. 2012).

Potential Operator Risk	Description
-	Potential risk does not exist.
1	Risk is present but has low impact and probability of occurring.
2	Risk is present but has low impact and high probability or high impact and low probability of occurring
3	Risk is present but has medium impact and medium probability of occurring.
4	Risk is present but has either medium impact and high probability of occurring or high impact and medium probability of occurring.
5	Risk is present but has high impact and high probability of occurring.



**Figure 22: Work Environment Metric (Faulkner et al. 2012)**

By identifying risky processes an organization can react and install proper controls to improve the safety of their employees as well as reduce the potential risks (Faulkner and Badurdeen 2014).

Sus-VSM was applied successfully by Brown et al. (2014) to various manufacturing systems showing how the method can provide a baseline for comparing the performance of different products and processes (Brown et al. 2014). Therefore, VSM and especially Sus-VSM is a powerful tool to measure the environmental impact of manufacturing processes and help companies visualize how this impact is related to the value stream of the product.

## **2.5.Environmental impact of manufacturing processes**

Manufacturing offers many opportunities for reducing environmental impact by utilizing resources more efficiently or by using new greener technology of manufacturing. Since there is a large variety of manufacturing technologies it can be difficult for decision-makers to select the most sustainable one. Analyzing processes information can help to identify the environmental impact and enables better decision making (Dornfeld 2011). The following subchapters include a comprehensive review of the environmental impact of the most common manufacturing processes. This includes the traditional group of machining which can be divided into: drilling, turning, milling, and grinding. In addition, the review includes casting, welding and coating processes.

### 2.5.1. Machining

Machining is any manufacturing processes in which a piece of raw material is cut into a desired shape by a controlled material-removal process. Therefore, machining processes are also known as subtractive manufacturing. The machining process can be characterized by the way the material removal is performed. Material can be removed by using a multitude of small abrasive particles or a defined edge cutting tool (Creese 1999). In general, machining processes have a high potential for generating negative externalities for the environment such as: improper disposal of cutting fluids, high energy consumption and health issues involving operators. Abrasive machining such as grinding is often used for finishing and high precision operations while machining with a defined edge cutting tool such as turning is common for semi-finishing parts. This situation of having a choice between two processes may be influenced by sustainability (Araujo and Oliveira 2012). The life cycle analysis aims to achieve a more comprehensive understanding of the environmental impact due to energy use and mass losses or waste. Therefore the system boundaries often only include the use phase of the machine tool as shown in the Input-Output diagram in Figure 23, but maintenance and disposal of the machine are excluded from the analysis.

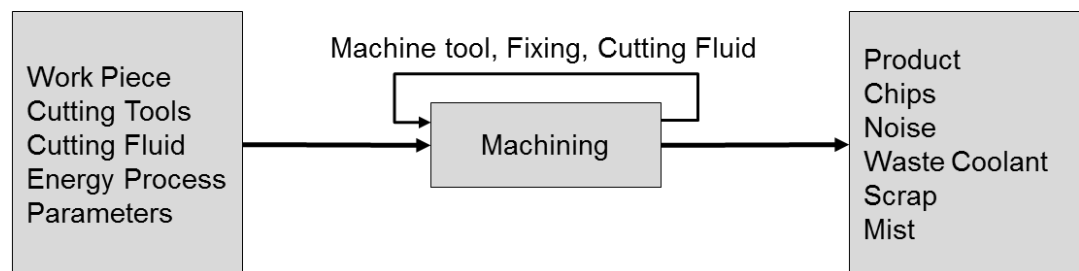


Figure 23: Input-Output diagram of Machining

## **Environmental impact due to energy consumption**

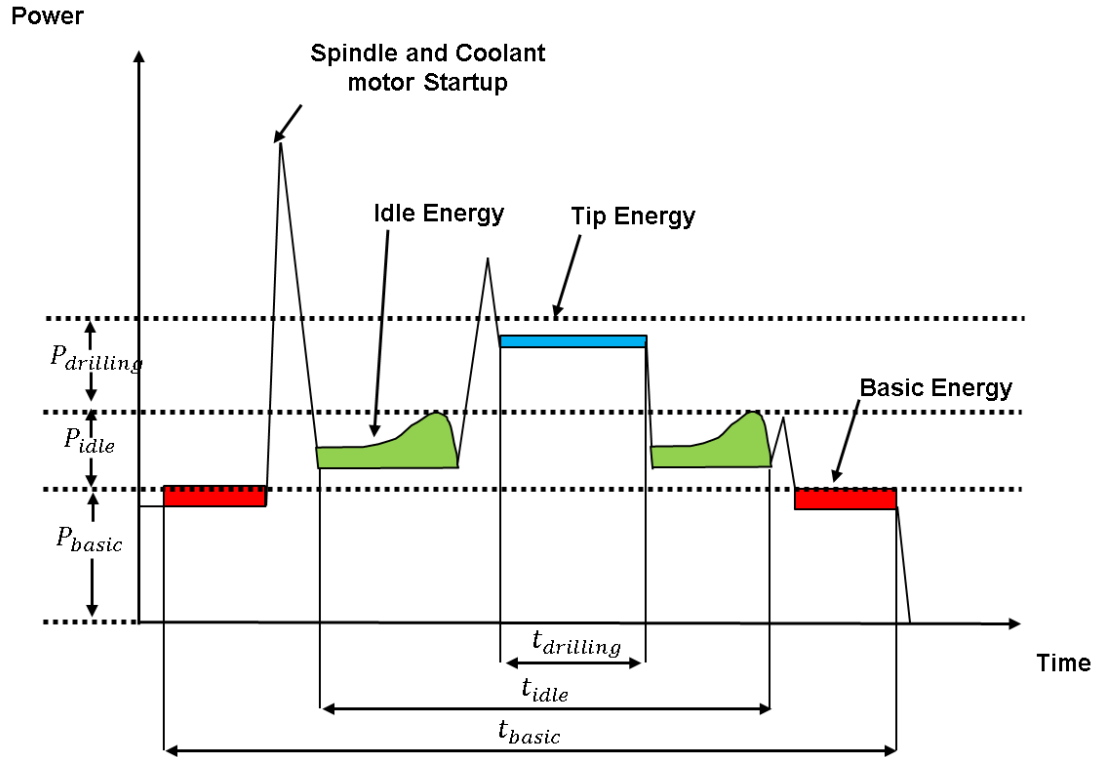
The required energy for machining depends on different variables. The variables can be ranked by their influence on the energy consumption (Dixit et al. 2012):

1. Material properties of the work piece
2. Feed rate  $f$  (mm/revolution)
3. Cutting speed  $V$  (m/min)
4. Size of the work piece
5. Cutting time
6. Coolant
7. Tool wear
8. Part holding fixture
9. Geometry and set-up

To calculate the required energy only the first five variables will be into taken account. In the first step, the machining time  $t_{machining}$  and power  $P_{machining}$  must be determined and can be calculated from the variables above. Depending on the given material, a representative cutting speed can selected from the literature. This optimum speed is affected by many factors such as (Kalla et al. 2010):

- composition, hardness and thermal conductivity of material
- width and depth of cut (roughing or finishing)
- efficiency of cutting fluid
- type and condition of the machine

Knowing the material, depth and length of the cut, the machining energy can be calculated. In addition to the actual machining process, the idle and basic energies must be included (Zein 2012).



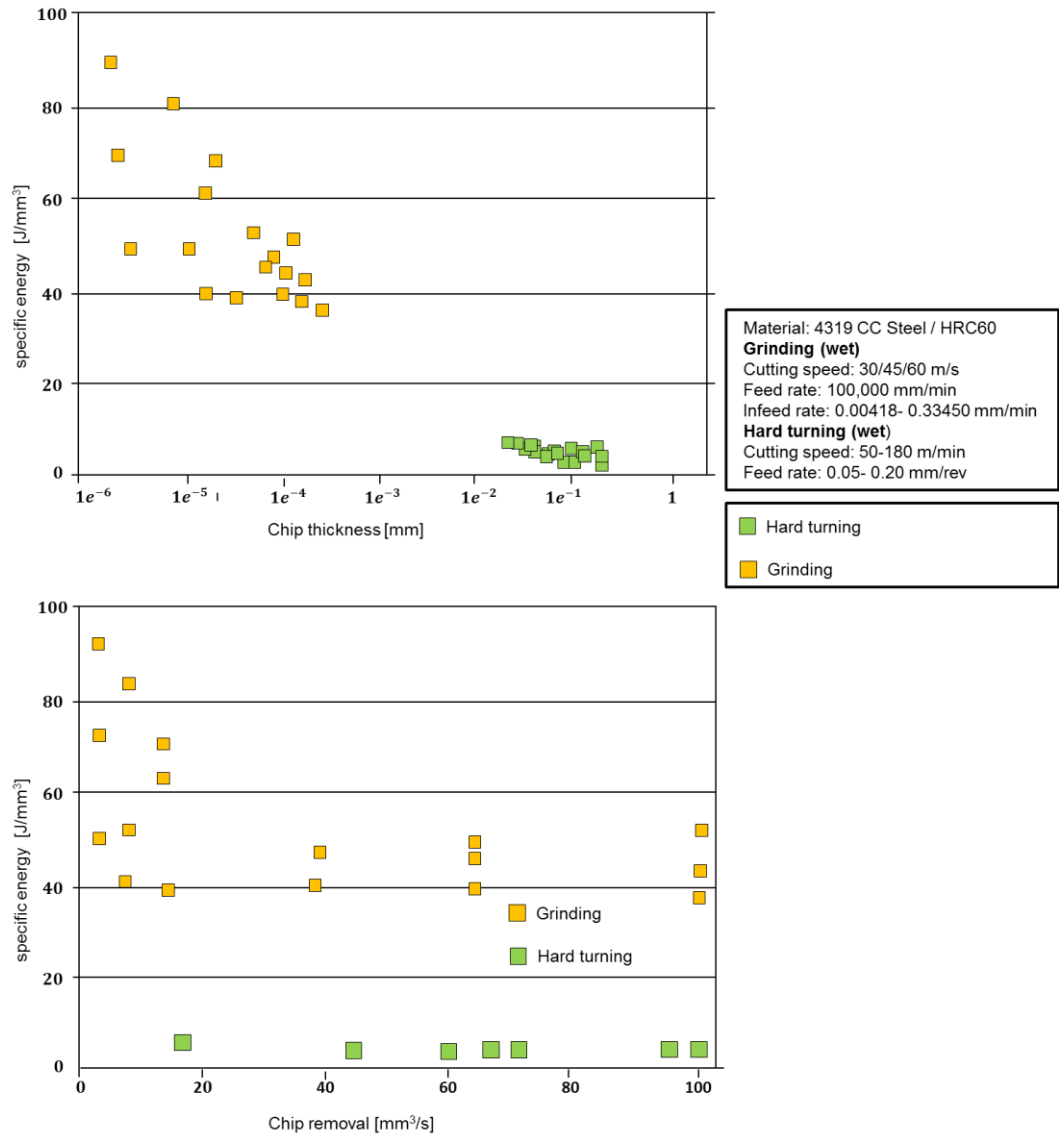
**Figure 24: Determination of power characteristics and energy requirements of machine tools (Kalla et al. 2010)**

According to Figure 24 the time component consists of  $t_{basic}$ ,  $t_{idle}$  and  $t_{drilling}$  which equals the actual machining time. Each time component matches with specific power consumption. By multiplying each power consumption with the matching time component the total energy consumption  $E_{total}$  can be determined (see Eq. 2) (Kalla et al. 2010).

$$E_{total} = P_{basic} * t_{basic} + P_{idle} * t_{idle} + P_{drilling} * t_{drilling} \quad (\text{Eq. 2})$$

The specific amount of energy that is needed to remove a certain volume of material differs for every machining process. In general, abrasive processes need a higher amount of energy to remove a specific material volume than processes with defined

cutting edges, due to high amount of rubbing actions from multiple cutting edges. For abrasive processes the converted energy can be divided into process energy, machine energy and energy consumed by peripheral components. Process energy includes the chip formation energy, deformation energy, friction energy and kinetic energy of the chips. As a result of internal and external friction, the majority of the mechanical energy is converted into heat. The process power for turning correlates to the spindle power of the machine and can be calculated by the cutting speed and tangential force. At a high chip thickness which occurs at a high material removal rate, the ratio of chip formation energy to friction and deformation energy is high. This results into a more effective chip formation and less thermal energy production. Hence, rising material removal rates increase the chip thickness while decreasing total energy consumption (see Figure 25).



**Figure 25: Specific energy comparison between hard turning and grinding (Aurich et al. 2013)**

These correlations are true for any abrasive process, but does not apply for machining processes with defined cutting edges (Aurich et al. 2013). The knowledge of specific cutting energies for different materials and cutting speeds help to determine the minimum amount of energy required to remove a certain amount of material. However, this energy requirement does not include the energy that is needed to run the



auxiliary equipment such as: automated tool changers or coolant pumps. Such equipment often requires a constant energy independent of whether or not a part is being produced. Therefore, it is important to calculate or measure the total system energy requirements for material removal. In an approach by Dahmus and Gutowski different machining scenarios were modelled to analyze the total energy requirements based on real machining data and various assumptions about operating and idle times. With this approach a rough estimation about the total energy requirements can be done (Dahmus and Gutowski 2004).

### **Environmental impact of waste stream**

The environmental impact due to waste stream during the machining process can be split up into solid, liquid and gas/aerosol. In case a dry machining process is used, there is no liquid waste stream (see Table 5).

**Table 5: Waste stream for drilling (Dixit et al. 2012)**

Waste Stream	Drilling
Gas/Aerosol:	<ul style="list-style-type: none"> <li>▪ Cutting fluid mist</li> <li>▪ Dust (dry machining)</li> </ul>
Solid:	<ul style="list-style-type: none"> <li>▪ Chips, worn tools</li> </ul>
Liquid:	<ul style="list-style-type: none"> <li>▪ Spent cutting fluids</li> </ul>

The work piece material loss due to machining can be specified as chip mass  $m_s$ . The chip mass can be calculated by multiplying the volume of material removed  $V_{removal}$  and the density of the work piece material  $\rho_{material}$ . The liquid

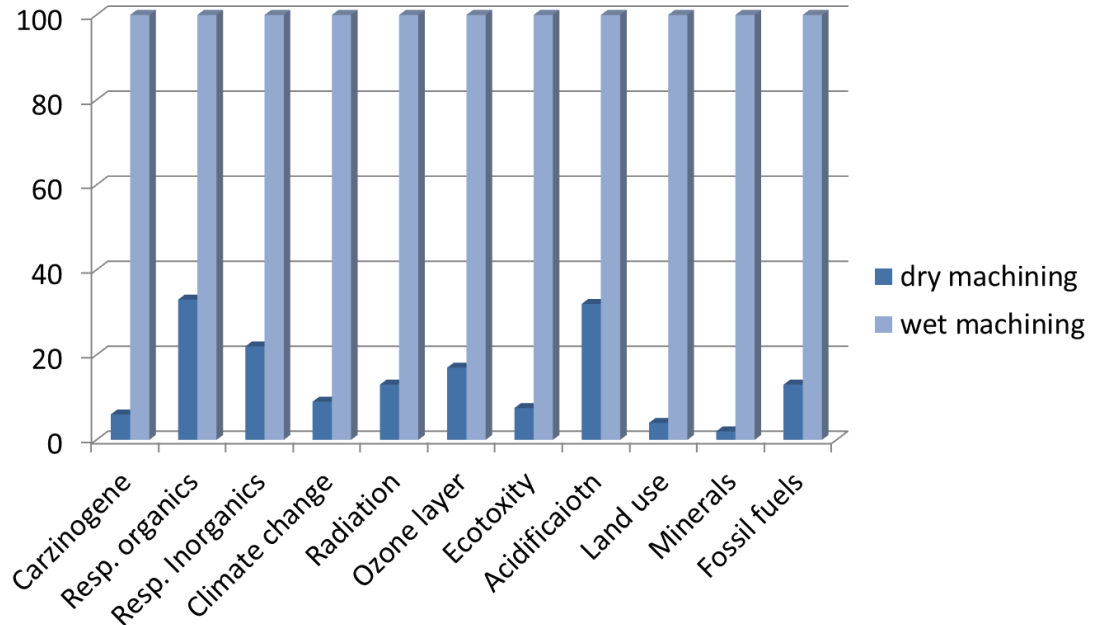
waste stream of machining operations relates to the cutting fluid that is spent. Cutting fluids have different functions. They are used to allow higher cutting speeds, improve the machined surface quality, reduce the wear of the tool and therefore prolong the tool life. In modern CNC machines, the cutting fluid is constantly recycled until the properties become insufficient (Dixit et al. 2012).

The environmental emissions that can be associated with the use of cutting fluids can be split up in seven categories: global warming potential (GWP), acidification, energy consumption, land use, solid waste, water use and toxic emissions to water.

A LCA performed by Clarens et al. revealed the fluid consumption of a CNC-machining tool over a year. Based on the assumptions that the number of parts produced per unit will not vary and the running time is based on a schedule (102 hr/week for 42 weeks/year) and a constant replacement of the cutting fluid, the mass loss of coolant can be calculated. The effective loss of cutting fluid is about 17g/min due to degradation and divides into 85 percent water and 15 percent cutting oil (Clarens et al. 2008). These oils are often petroleum-based and are difficult to dispose. In reaction with the environment they cause water, air and soil contamination. Moreover, the exposure of those fluids during machining may lead to serious health issues for machine operators (Dixit et al. 2012).

A more detailed LCA was conducted by Lodhia (2007), who analyzed the impact of cutting fluids in machining processes. The comparison of dry and wet machining within the analysis shows that the energy consumption for dry machining is eight percent less than the energy required for wet machining processes and generates

about 7 times higher environmental impact (Lodhia 2007). Figure 26 compares the different environmental impacts for wet and dry machining.



**Figure 26: Comparison of LCA results for wet and dry machining (Lodhia 2007)**

Therefore, dry machining should be favored since it is the best solution from an environmental point of view, and options, that eliminate or minimize the use of cutting fluids should always be considered (Dixit et al. 2012). Nowadays new vegetable-based oils are being tested to replace the existing conventional petroleum-based cutting fluids (Boubekri and Shaikh 2012).

### **2.5.2. Casting**

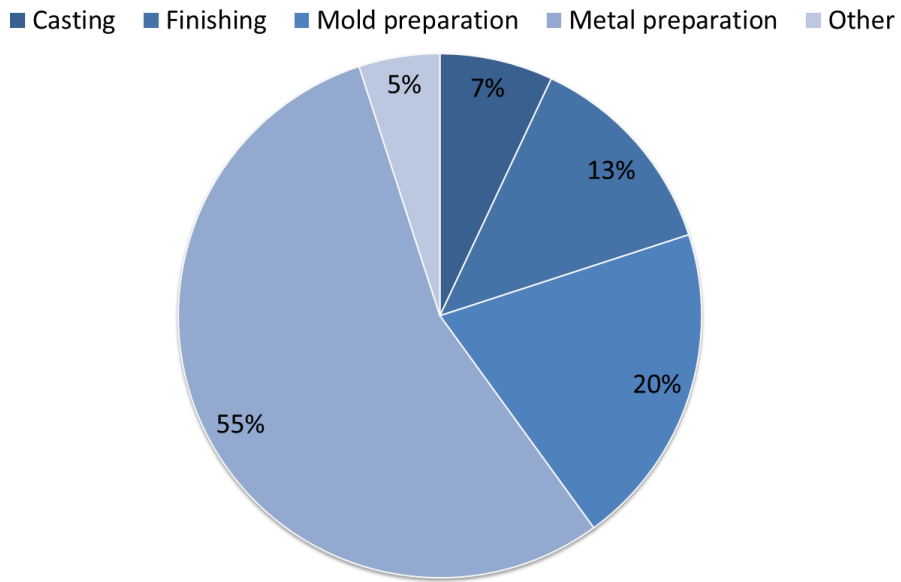
Casting generally implies metal casting, but polymers sometimes are referred to as being cast. However, castings are poured above the melting point so that the liquid material has low viscosity and high fluidity, and gravity feeding is common. Casting polymers cannot be fed by gravity since they do not reach the same high fluidity as

metal. Two very common techniques of casting are sand and die casting (Creese 1999).

In general, casting is an energy intensive manufacturing process. Most of the energy is used to melt the metal. In addition, casting needs a lot of material. The creation of nonpermanent molds, such as those used for sand casting, demands an exceptionally large amount of additional material. It becomes evident that the environmental impact of casting has to be analyzed (Gutowski and Dalaquist 2004).

### **Environmental impact due to energy consumption**

According to the Manufacturing Energy Consumption Survey (MECS) by Energy Information Administration (EIA) the metal preparation needs 55% of the energy within the casting process (see Figure 27). The total energy requirement per 1 kg of material is around 2,93 kWh, but varies by metal and furnace type. This relatively high value is due to an average efficiency of 40% for furnaces (Dalaquist and Gutowski 2004).



**Figure 27: Energy requirements by stage. The total energy requirement is around 10 MBtu/ton, but varies metal an furnace type (Dalaquist and Gutowski 2004)**

### Environmental impact of the waste stream

Comparing the waste stream for die and sand casting shows that they have similar waste outputs (see Table 6).

**Table 6: Comparison of the waste stream of different casting types (Dalaquist and Gutowski 2004)**

Waste stream	Type of casting process	
	Sand casting	Die Casting
Gas/Aerosol	<ul style="list-style-type: none"> <li>▪ Dust</li> <li>▪ Metallic particles</li> </ul>	<ul style="list-style-type: none"> <li>▪ Volatile organic compound (VOC)</li> </ul>
Solid	<ul style="list-style-type: none"> <li>▪ Green sand incl. binder</li> <li>▪ Scrap metal</li> </ul>	<ul style="list-style-type: none"> <li>▪ Scrap metal</li> </ul>
Liquid	<ul style="list-style-type: none"> <li>▪ Cleaning chemicals</li> <li>▪ Coatings</li> </ul>	<ul style="list-style-type: none"> <li>▪ Soluble oil cutting fluid</li> <li>▪ Water diluent</li> </ul>

The first steps to analyze are the die or mold preparation. A high amount of energy and metal is needed to create the die. In order to cut the material out of the metal stock and form the die, machining is required. As already mentioned in Chapter 2.5.1, machining requires lubricants and cutting fluids. The fluids are often oil-based and release hazardous volatile organic compounds (VOC). However, the resulting emissions for creating a die can be split in between 15,000 and 500,000 castings over the typical lifetime of a die (Dalaquist and Gutowski 2004). It can be estimated that around 1kg of cumulative VOC emissions are produced per ton of produced casting (Roberts et al. 2003).

In comparison, the mold preparation for sandcasting needs to be done for every casting since every mold can only be used once and is destroyed. Green sand to create the molds can be recycled, but has to be filtered to remove binder remnants and fine grained particles. It can be estimated that for each ton of cast metal about 5.5 tons of sand is needed. About 10% of this sand cannot be used for remolding and has to be disposed, which shows the high amount of solid waste flow. Besides the green sand, the included chemical binders that are used to resist high pressure during the casting process have a major environmental impact. They are associated with as hazardous air pollutants (HAPs) (Gutowski and Dalaquist 2004).

During the casting process most environmental impact is related to the release of HAPs due to dust and metal fumes. Moreover, sand casting also produces organic emission which occurs when the metal comes into contact with the sand and binder, which continues until the part is completely cooled down (Yilmaz et al. 2014).

After the casted material cools down, the part has to be finished to meet the desired quality. During this stage both casting techniques are very similar. Therefore, all runners and sprues that are used to funnel metal into the mold have to be removed by machining which produces scrap metal and other waste that is related to the usage of those machines (see Chapter 2.5.1) (Dalaquist and Gutowski 2004). A detailed overview of the input and output flows for iron casting is given by Yilmaz et al. in Figure 28.

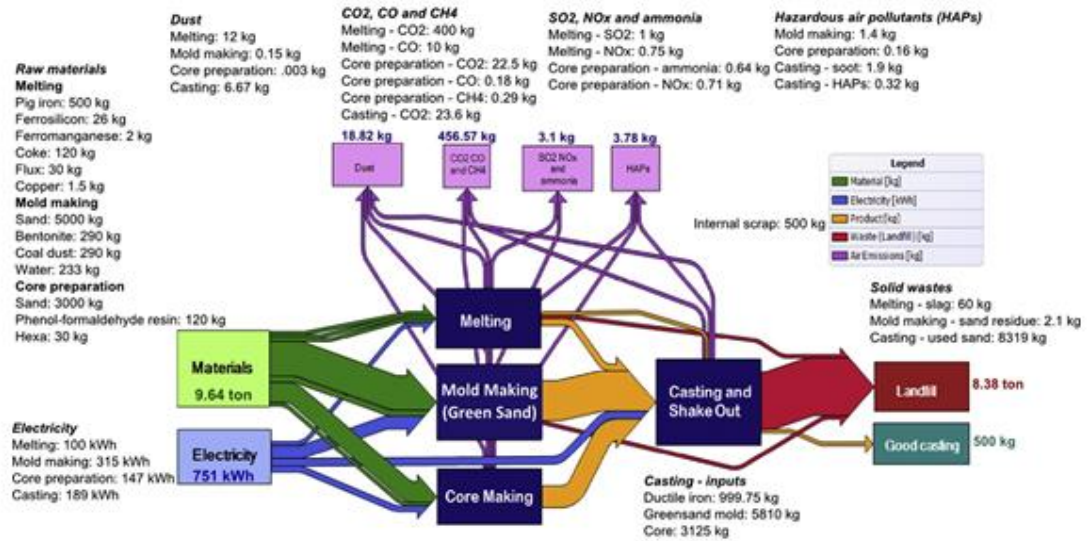
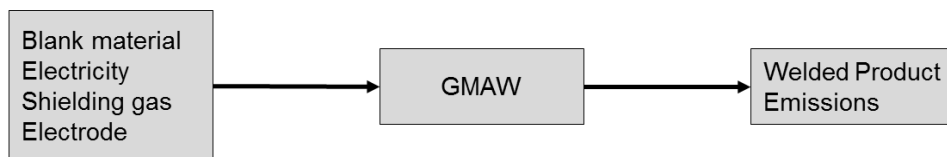


Figure 28: Material and energy flows used for Sand Casting (Yilmaz et al. 2014)

### 2.5.3. Welding

Welding is an omnipresent process, which is used across at companies worldwide for assembly of components of products. There are to different categories of welding processes: fusion welding and solid-state welding. Fusion welding is defined as the coalescing of materials by means of heat. The thermal energy required for melting the materials is usually supplied by chemical and electrical means. Filler metals, which

may or may not be used in the weld area during welding lead to another differentiation: consumable- and non-consumable- electrode arc welding. In arc welding, the heat required is supplied from electrical energy. The two most common arc- welding processes are Shielded metal-arc welding (SMAW) and Gas metal-arc welding (GMAW). GMAW uses an arc that is struck between a consumable wire electrode a workpiece. The weld area is shielded by an atmosphere of inert gases such as argon, carbon dioxide or a mixture of both. The consumable bare wire is fed automatically through a nozzle into the weld arc (Kalpakjian and Schmid 2013).

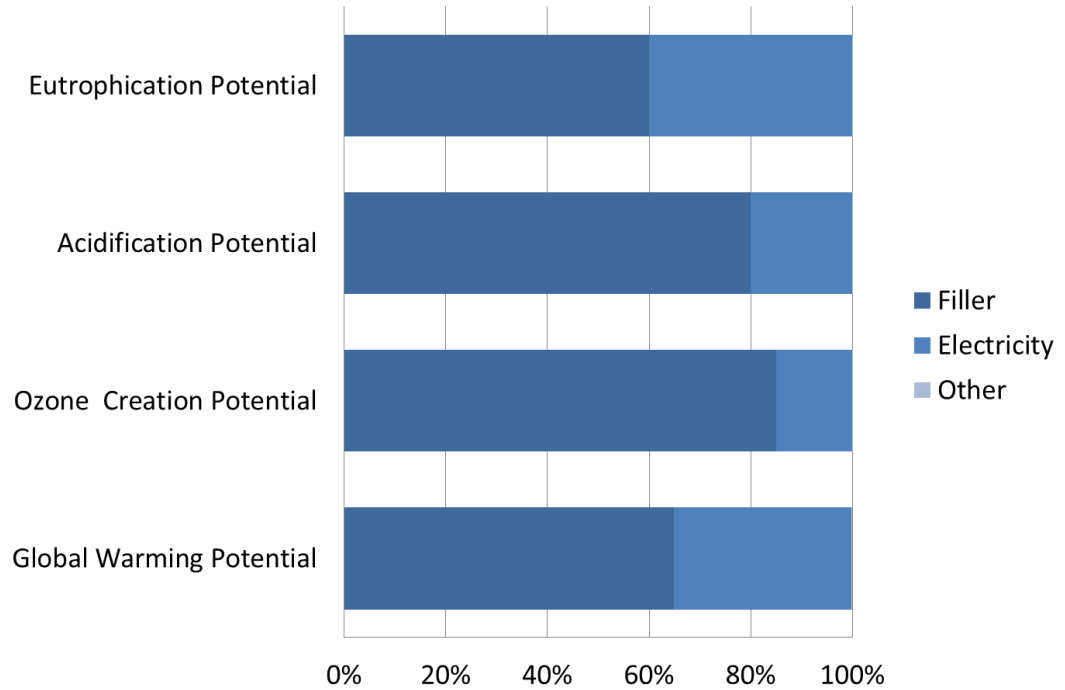


**Figure 29: Material flow for Gas metal-arc welding**

Recent LCAs conducted by Shrivastava et al. and Chang et al. on gas metal arc welding on aluminum and steel, revealed the environmental impact of GMAW according to the material flow of inputs and outputs (see Figure 29). Although the environmental impact of welding varies with the material and equipment used, these studies help to get an overview (Shrivastava et al. 2015).

According to Chang et al. the most relevant impact indicators for assessing welding are: global warming potential, acidification, photochemical ozone creation potential, and eutrophication. As shown in Figure 30, the main contributors on these indicators are the consumed electricity and filler material e.g. electrodes (Chang et al. 2015).





**Figure 30: Contribution on environmental impact indicators (Chang et al. 2015)**

The fumes that are generated during welding processes are very important for the environmental impact. This by-product is a complex mixture of metals volatilized from the used filler material. It is often associated with different types of lung diseases and therefore a potential health risk for humans (Chang et al. 2015).

#### **2.5.4. Coating**

Coatings are used to protect manufactured components from thermal or corrosive degradation and enhance the aesthetic appeal. The large variety of coating techniques makes it difficult to select the right coating. Besides considering the operating conditions or costs it becomes more and more important to include the environmental effects of coating since existing and announced environmental legislations claim the

reduction of volatile organic compounds and other hazardous waste (Asthana et al. 2006).

## **2.6. Computer Aided Cost Estimation**

In the past, the assessment of manufacturability and production costs has been conducted based on the construction of prototypes and physical tests during the development of a product (Ostwald 1992). Manufacturing prototypes often requires specific tools which have to be designed and produced, and then future design changes require tool adjustments or even replacement by a new tool. This part of product development can be very time consuming and costly. One approach to address this problem is by using Computer Aided Engineering Cost (CACE) software which can help to estimate product costs and make statements about manufacturability. There exists already a large variety of software packages on the market, however they are mainly based the Activity-Based Costing (ABC) or on the analysis of 3D-CAD data to calculate the costs of production (Niazi et al. 2006).

Activity-Based Costing is focused to allocating overheads for each process step during production based on their origins of consumption. Software based on ABC is often very flexible and suitable for different manufacturing processes. The user can select from different machine types and adjust process data such as cycle time, the amount of scrap or energy consumption according to his individual machine (Drury 1992). This makes this type of software very flexible since it can virtually model every manufacturing process. However, CACE software based on ABC requires a high availability of reliable and accurate production data, as well as high level of user

knowledge (Micro Estimating Systems 2012). In the following section the three most important software tools are presented.

### **DFM Concurrent Costing Software**

The DFM Concurrent Costing 2.3 software is part of the software package "Design for Manufacture and Assembly" of the company Boothroyd Dewhurst, Inc. and is divided into the programs "Design for Assembly" and "DFM Concurrent Costing". The software is a hybrid tool that generates cost estimates based on the 3D-CAD files or by manual entry of all input data and definition of assembly steps by the user. DFM Concurrent Costing uses a library with a wide range of equipment for machining, forging, casting, and various assembly operations (Boothroyd Dewhurst 2015).

### **Siemens Teamcenter Pro Calc**

The Perfect ProCalc software exists since the year 2000 and was developed by the company Tsetinis. During that time the software was mainly to estimate costs in the German car industry. In 2012, the Siemens software was bought and integrated into Siemens software package called Siemens PLM. Perfect ProCalc uses the ABC approach to analyze costs and has an extensive database of some 300 regions and more than 3,000 types of machines. This allows rapid evaluation of cost effects of the transfer of production from regions with high labor costs to other low-wage countries. Perfect ProCalc also provides tools for calculating cycle times and allows the user to import available documents (e.g. 2D drawings, photographs and Excel Calculation) available (Siemens PLM Software 2015).

## **aPriori**

The software aPriori developed by a company of the same name, estimates cost based geometric data derived from a 3D CAD file. aPriori is focused on the costing of various metals and plastics including their processing and surface treatment. A special feature of aPriori is the Virtual Production Environment (VPE), which includes pre-configured setups for different regions regarding rates for labor, cost per square meter, energy, as well as typical overheads of suppliers. In the standard library eight other VPEs including the United States are available. Furthermore, aPriori is the only CACE software that supports the user by choosing between different manufacturing processes based on generic data. This is a very helpful feature when new product designs or manufacturing lines have to be planned while detailed cost information is not available (Apriori Inc. 2015).

## **2.7. Need for a framework to assess sustainability and cost**

This chapter demonstrated that the manufacturing industry is a main consumer of natural resources and main producer of environmental impacts. Knowing this makes companies highly responsible towards their environment. Sustainable manufacturing is one way to decrease the environmental impact of a company. Before a company can start to enhance their processes towards more sustainable manufacturing, it is necessary to identify unsustainable manufacturing steps. Therefore, it is important to evaluate the environmental impacts of each manufacturing step in order to derive how they contribute to the environmental impact of the complete manufacturing process.

Comparing those measurements with data from a cost analysis helps to reveal potential cost savings that go along with sustainable manufacturing.

Even though the literature review from Chapter 2 indicates that several tools and frameworks are already available to assess sustainability, it also demonstrates that results vary depending on the subject of investigation and the required insight knowledge and efforts to use those tools is significant. Moreover, most frameworks focus primarily on a single measurement such as energy or water consumption.

## CHAPTER 3 – METHODOLOGY

In order to fill the gap of a missing method that combines different measurements for the environmental impact and costs, it is necessary to develop a framework that includes both aspects. Therefore, it is important to specify the purpose of the framework in the beginning. Generally, the study aims to develop a framework to assess product sustainability and cost performance. Furthermore, it is the goal that the framework supports small companies by giving them guidance of how to approach LCA and identifying the environmental impacts of current and future state manufacturing processes. An overview of the methodology is given in Figure 31. By comparing the LCA results with costs, overlaps can be derived. In the first step suitable indicators for sustainability have to be identified.

In the next step, primary data is gathered from the product of the case study. Since the acquisition of environmental impact data is one of the most critical and cost intensive steps within LCA, it is important to limit the number of measurements to an easy accessible level. However, it must be ensured that the framework still leads to viable results and matches the basic requirements of LCA according to ISO 14040.

Analyzing LCA data is very complex, so appropriate software is necessary to support the assessment of environmental impacts. Therefore, different LCA-software packages are compared and the best suitable software is selected.

In the next step, LCA is conducted to assess the environmental impact of the current state manufacturing processes. Based on these results, alternative future state models are developed to improve the sustainability of the product by decreasing its

environmental impact. After the models are developed a LCA is conducted for each model and the results are compared.

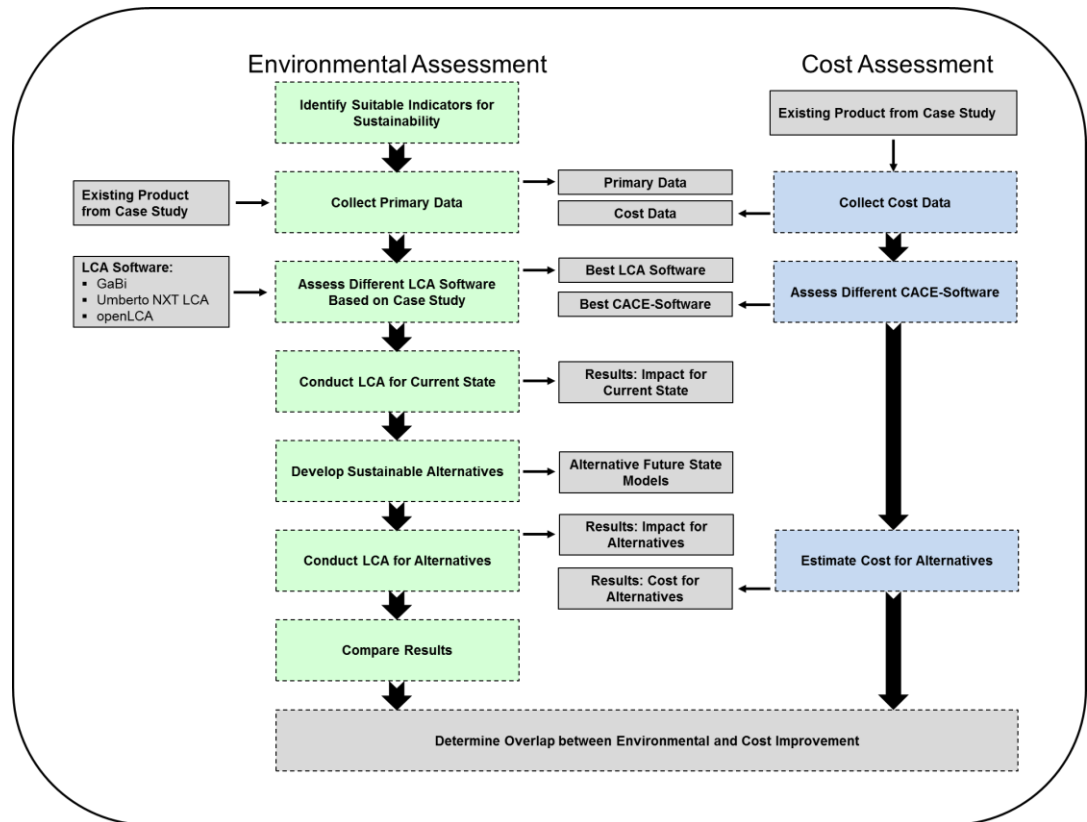


Figure 31: Methodology steps of this study

In addition to the environmental assessment the costs of the product have to be assessed. In the first step, the cost data is gathered. For the existing product current state, costs data is available. To estimate costs for alternative future state models the support of CACE-Software is necessary. In order to find suitable software, different CACE-Software packages have to be assessed. Then, this software is used to estimate the cost of the alternative models. Finally, the results of the environmental and cost

assessment are compared to determine the overlap in cost savings and environmental impact improvement.

### **3.1. Suitable Indicators of Sustainability**

This chapter presents general criteria for indicators for sustainability. Based on those criteria appropriate indicators are derived.

#### **3.1.1. Basic criteria for Indicators**

Indicators have to meet certain criteria and user must be able to measure, monitor, and record them on a regular basis. There is a large variety of possible sustainability indicators that can be found in literature. However, not every indicator is relevant for manufacturing processes or are easy to measure. Therefore, suitable indicators have to be identified. Indicators are simple measures that represent a state or condition of something. Within this study, indicators are defined as “information used to measure and motivate progress toward sustainable goals” (Ranganathan 1988).

According to Robertson, the selection of indicators should be based on the goals that are identified for the assessment. In addition, there are other concerns that should be taken into account when selecting indicators. Sustainability indicators should be measurable, which means that they are quantitative rather than qualitative. Furthermore, they should be relevant for the goals that are pursued. They should be based on data that is available, reliable and easy accessible (Robertson 2014). The US Environmental Protection Agency (EPA) and Feng et al. have established a catalog of criteria for potential sustainability indicators (see Table 7).



**Table 7: Criteria for Sustainability Indicators (Feng et al. 2010; EPA 2007)**

Criteria	Explanation
Relevant	Indicators have to fit the purpose of measuring sustainability performance and provide useful information on it.
Measureable	Indicators need to be capable of being measured quantitatively or qualitatively and defensible in a scientifically way.
Understandable	Indicators should be easily understandable by people who are no experts.
Manageable	Indicators are limited to the minimal number required to meet the measurement purpose. At the same time, organizations should be able to make decisions on the number and type of indicators to apply.
Reliable	Information that is provided by the indicators must be trustworthy.
Data accessible	Indicators have to be based on accessible data. This data should be easily collectable from existing sources and at modest cost.
Timely manner	Measures should be taken within an appropriate interval of time. Frequent measuring should be possible to enable timely, informative decision making.

Taking these criteria as a base for the content of the indicators, there are further characteristics regarding the format and structure of indicators (Veleva and Ellenbecker 2001):

- Identification: Indicators should be organized either alphabetically or numerically.
- Name: Indicators need to be clearly stated.
- Definition: Indicators should be defined with their essential characteristics and functions.
- Unit of measurement: The value of indicators needs to be specified by a unit of measurement (e.g. kilograms, tons, percent, hours)
- Type of measurement: Indicators can be measured either quantitatively or qualitatively and further can be either absolute (e.g. total energy used per year) or adjusted (e.g. energy used per unit of product per year)

- Period of measurement: Indicators have to be measured over a defined period of time (e.g. year, month, work shift)

The listed criteria in Table 7 and characteristics that are listed above are helpful to select the right indicators and order them appropriately.

### **3.1.2. Identifying Indicators for Sustainability**

According to the three different dimensions of sustainability, environment, social and economy suitable indicators for each dimension have to be derived. Every dimension is directly related to specific issue(s).

#### **Issues for Environmental Sustainability**

The environmental impact is traditionally the most crucial dimension in terms of sustainability, and it is the dimension discussed in most detail in the literature. Hence, a lot of different tools are available that address this dimension and evaluate environmental sustainability. In general they can be divided into two main issues:

- Natural resources: This issue evaluates the use of energy, water and raw material as well as the amount of waste that is being created during the production of a product.
- Pollution: This issue assesses the contribution of the manufacturing process to climate change and global warming.

#### **Issues for Social Sustainability**

Issues related to the social dimension of sustainability are becoming more and more important for the public. Therefore, there are different issues that belong to the social dimension of sustainability:

- Health and Safety (Human toxicity)
- Work satisfaction and development
- Equal opportunities and perspectives

However, only health and safety is taken into account with regard to manufacturing processes. It focuses on the security and wellbeing of employees that could be exposed to hazardous materials and substances.

### **Issues for Economic Sustainability**

Issues regarding the economic dimension of sustainability are focused on the financial stability or profit of the evaluated subject. Furthermore, economic sustainability often includes issues related to investment and expenditures on future development. Meanwhile, none of those issues relates directly to specific manufacturing processes and therefore will not directly be included as indicators for sustainability. However, costs are included as parameters in the CACE-simulation.

After defining the different issues for each dimension of sustainability and the general criteria for indicators, the next step is to define a number of key indicators that meet all the criteria. Generally, this research aims to use quantitative indicators, since they are more objective and less biased than qualitative ones. It should also be possible to express each indicator in relative terms and not only in absolute terms to ensure that manufacturing steps can be compared easily. The identified key indicators for this framework are summarized in Table 8.

**Table 8: Key sustainability indicators**

Dimensions	Themes	Indicators	Unit
Environment	Natural resources	1. Material use	Kg
		2. Energy use	kWh
		3. Freshwater consumption	m <sup>3</sup>
		4. Waste generation	Kg
	Pollution	5. Global warming potential	Kg CO <sub>2</sub>
		6. Acidification potential	Kg SO <sub>2</sub>
Social	Health and Safety	7. Human toxicity	Kg 1.4-DCB

While Table 8 gives an overview of all indicators, a more detailed description of each key sustainable indicator is presented in the following sections. The description includes the significance for manufacturing, the goal in terms of sustainability and the calculation or measurement of the indicator.

**Indicator 1: Material use – total consumption of non-renewable resources**

- **Relevance:** The depletion of non-renewable resources such as metal, minerals and fossil fuels is becoming a critical factor for traditional economic growth on a global scale. By reducing the material use in manufacturing a more sustainable development can be achieved.
- **Goal:** Reduce the total material consumption
- **Measurement/calculation:**

The total consumption of non-renewable resources is measured by adding up all material that is used within one manufacturing step.

**Indicator 2: Energy use – total consumption of non-renewable energy resources**

- **Relevance:** A main goal for sustainable manufacturing is to reduce the energy consumption of non-renewable resources such as coal and other fossil fluids. More efficient manufacturing processes and switching to renewable energy resources, such as sun or wind. Moreover, energy from non-renewable resources is directly related to increasing air pollution, depletion of fossil fuels and global warming. As explained in chapter 2, manufacturing processes are often very energy intensive, which makes this indicator so significant for this framework.
- **Goal:** Reduce the energy consumption
- **Measurement/Calculation:** The energy use can be measured with different devices, if the power supply is accessible. In case the power supply is not accessible, the energy use can be roughly calculated by measuring cycle time and multiplying it with the theoretical maximal energy demand given by the manufacturer of the machine.

**Indicator 3: Waste generation – total generation**

- **Relevance:** According to EUROSTAT, the United States generates 7,080,000 thousand tons annually only during manufacturing/production (Twardowska et al. 2004). Similar amounts of waste are generated in

countries all over the world. This high amount of waste causes major environmental problems such as pollution and the release of toxic substances that cause harm to humans and the ecosystem.

- Goal: Reduce the waste generation
- Measurement/ Calculation: The amount of solid waste generated per process unit. The waste is either measured directly or by measured using the weight the blank part before manufacturing and afterwards. The weight difference is used to measure the generated waste.

#### **Indicator 4: Global Warming Potential (GWP)**

- Relevance: Global warming potential measures the contribution of a particular gas to global warming, by comparing this gas on a relative scale with carbon dioxide. As shown in Table 9 , carbon dioxide is assigned to a GWP value of 1. Global warming is related to warming up sea water and melting glaciers, which changes the earth ecosystem significantly. Manufacturing often contributes large amount of emissions to global warming.
- Goal: Reduce emissions and slow down the process of global warming
- Measurement/ Calculation: GWP is difficult to measure. However, the GWP can be calculated by measuring the quantity of emission released during the manufacturing process and multiplying it with the equivalent factor of that emission relative to carbon dioxide (see Table 9). This calculation is often done within the used LCA-Software packages.

#### **Indicator 5: Acidification potential (AP)**

- **Relevance:** Acidification potential measures the contribution to the acidification of a particular gas and compares it at a relative scale with sulfur dioxide. As shown in Table 9, sulfur dioxide is assigned a value of 1. Gases with acidification potential can be absorbed by plants and soils, which then lead to decreased biomass and poor soil quality. Furthermore, surface water may be acidified, resulting in poor water quality.
- **Goal:** Reduce emissions of acid gases.
- **Calculation/Measurement:** AP is difficult to measure. However, the AP can be calculated by measuring the quantity of emission released during the manufacturing process and multiplying it with the equivalent factor of that emission relative to sulfur dioxide (see Table 9). This calculation is often done within the used LCA-Software packages.

**Indicator 6: Human Toxicity (HT)**

- **Relevance:** Hazardous materials are mainly chemicals or mixtures of chemicals that are toxic, flammable or can cause other injury to humans. In order to protect worker's health and safety they should be protected from those types of materials.
- **Goal:** Reduce usage of hazardous material.
- **Calculation/Measurement:** HT is difficult to measure. HT describes the expected health effects of materials depending on the concentration and probability of effects. This calculation is often done within the used LCA-Software packages

**Table 9: Identifying weighting factors for emissions**

Emissions	CO <sub>2</sub>	SO <sub>x</sub>	NO <sub>x</sub>	CH <sub>4</sub>	HKW	NH <sub>3</sub>	N <sub>2</sub> O	HCl
GWP (CO <sub>2</sub> -equivalent)	1			25	4750		298	
AP (SO <sub>2</sub> -equivalent)		1	0.7			1.88		0.88

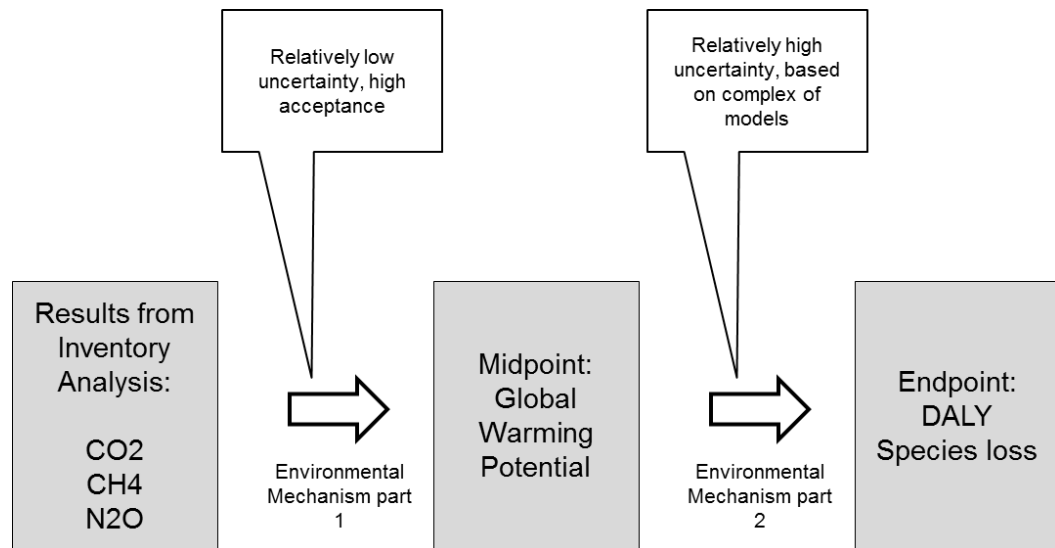
### Characterization methods for LCA

After suitable indicators for the framework are chosen, they have to be integrated into the framework. Therefore, a characterization method has to be chosen. Characterization methods address indicators to different impact categories. They include different characterization factors that are applied to convert an assigned life cycle inventory result to the common unit of the category indicator. Characterization methods can be applied using midpoint and endpoint methods. The midpoint method is a characterization method that provides indicators for comparison of environmental interventions at a level of cause-effect chain between emissions/resource consumption and the endpoint level. The endpoint method is an attribute or aspect of natural environment, human health, or resources, identifying an environmental issue giving cause for concern (ISO 14040) (see Figure 32). Hence, the method (or damage approach) is a model that provides indicators at the level of areas of protection (natural environment's ecosystems, human health, resource availability) or at a level close to the Areas of Protection level.

Common characterization methods are the different types of ReCiPe. They are based on midpoint, endpoint or a combination of midpoint and endpoint approaches. ReCiPe Midpoint uses midpoint and ReCiPe 2008 uses a combination of both



approaches. For example, the gas methane is classified to the midpoint impact category climate change. The reference material of this category is kg CO<sub>2</sub> to air.



**Figure 32: Example of a midpoint-endpoint model**

The quantity of methane is characterized with a certain factor of 25 to an equivalent quantity of CO<sub>2</sub>. After that, all determined equivalents of materials which have an impact on climate change are summed. The final value is the result of the midpoint approach and indicates the global warming potential of the related product. To continue to the endpoint indicator, the midpoint indicator is allocated to damage categories. Each indicator of the midpoint classes is re-characterized with fixed factors to the indicators of the damage categories. For example, the indicator for damage to ecosystem diversity is loss of species during a year (Goedkoeep et al. 2013)

The example midpoint class with its indicator for global warming potential is connected to damage to human health such as Disability adjusted life years (DALY) and damage to ecosystem diversity in form of loss of species.

The last step of the ReCiPe endpoint method is called normalization. The endpoint damage indicators are converted to the unit points with weighting factors (Althaus et al. 2010). The factors depend on three different cultural perspectives. The individualist is optimistic that future technology is able to solve today's problems. In contrast to that, the egalitarian is cautious and rates impacts more negatively. In the middle lies the hierarchist perspective (Goedkoop 2014). As this is the weighting which is often used in scientific models, the hierarchist perspective is applied in this study, too. After the normalization process, one point represents the thousandth part of the annual ecological load of an average European (Herrmann 2010).

The existence of methods addressing midpoints and others addressing endpoints is justified and is legitimate given that the choice of method is intricately linked to the product/activity under assessment. However, for this research the ReCiPe Midpoint approach is chosen, since this approach is highly accepted for scientific research because of the relatively low uncertainty. Furthermore, this approach expresses the environmental impact in reference indicators such as m<sup>3</sup>, kg CO<sub>2</sub>, kg SO<sub>2</sub> or 1,4-Dichlorobenzene (DCB) and can be compared more easily with other references. According to the indicators in Table 8, following indicators were selected from the ReCiPe Midpoint approach:

- Climate change, Global Warming Potential (GWP100) in kg CO<sub>2</sub> equivalent
- Human toxicity (HT) in kg 1,4-DCB equivalent
- Acidification potential (AP100), AP 100 in kg SO<sub>2</sub> equivalent

All other indicators, such as material use, waste generation and energy consumption can be derived directly and do not need an equivalent ReCiPe indicator.

## 3.2. Collect Primary Data

The collection of primary data is an important as it is the base for the conducted LCA. However, all data gathered within this study was manipulated by a key multiplier to ensure the integrity of the manufacturer and does not represent the real manufacturing data.

### 3.2.1. Data collection of CNC machines

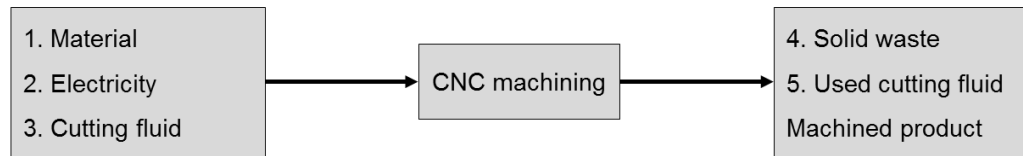
The CNC machines used in this case study is an Okuma LB3000 EX with an additional mist collector (see Figure 33).



Figure 33: Okuma LB3000 EX CNC machine

The CNC machines are used to manufacture different components of the product: including the housing, mounting cover and eccentric. In order to assess the environmental impact of the manufacturing process, the concept of a unit operation is applied, that indicates a conversion of material and chemical inputs into a transformed

material and chemical output. According to this, the following transformation of input to output derives five LCI characteristics (see Figure 34).



**Figure 34: General Input-Output diagram for CNC machining**

The input materials for this machine are blank housings, blank mounting covers (both casted aluminum) and blank eccentrics (casted iron). Before those pre-casted parts can be assembled, they have to be machined to meet required tolerances. Therefore, different cutting tools, cutting fluid and energy are needed.

### **Energy consumption**

The energy consumption is calculated based on the constant voltage (220V) and the measured amperage during the machining process. To measure the amperage a clamp meter is connected to one phase of the power supply. Since the clamp meter can only measure the current amperage but not save it over the complete manufacturing time, two video cameras are used to film the display of the clamp meter and the manufacturing process. By matching the footage, the energy consumption of the complete manufacturing process can be derived. This setup is used to measure the energy consumption for every manufacturing step.

The housing, mounting cover and eccentric are all manufactured on the CNC machine A, which is equipped with an additional mist collector.

### **Material usage and solid waste generation**

To measure the material usage all blank components are weighed on a scale before they are machined. After the machining all components are weighed again, and the difference of weight is accounted as waste. In the case study, most of the waste is scrap metal. Since most of the blank components have slightly different weight and dimensions for each component, five samples were measured. Based on the measurements of the different samples, a mean value for each component and manufacturing process is derived.

### **Cutting fluid consumption**

The fluid is used as a coolant and also lubricates the cutting surfaces. It is difficult to measure the cutting fluid consumption because it is constantly recycled within the CNC machine until the properties of the fluid become inadequate. Moreover, due to other losses such as evaporation and spillage, the cutting fluid has to be replenished on a regular basis. To estimate the cutting fluid consumption, an approach by Clarens et al. was chosen. It is assumed that the number of parts produced per unit time will not vary depending on the cutting fluid replacement. In Clarens approach, the machining time associated with one year of manufacturing and is based on a schedule of 102 hours of machining per week. The CNC machine used in his studies was equipped with a 208 L (55 gallon) tank to provide cutting fluid to the cutting zone. The 208L/machine is recycled within the process until it is disposed of after two weeks. Assuming cutting fluid is used 204 hr/ 2 weeks, then the cutting fluid loss is 208L per (204\*60) minute, which is 0.017 L/min or about 17 g/min as the effective loss of cutting fluid due to degradation (Clarens et al. 2008).

$$\frac{208 L}{102 \text{ hours} * 2 \text{ weeks}} = 1.019 \frac{L}{h} = 0.17 \frac{L}{min} \quad (\text{EQ. 2})$$

This approach is used for this case study and the values are adjusted according to the process parameters of the cutting fluid and the typical operating procedures at the company..

### 3.2.2. Data collection for welding

In this case study GMAW welding is used to weld the manufactured shaft to the rotor as part of the motor assembly. The input-output diagram shows the main three LCI characteristics: electricity, used electrodes and shielding gas (see Figure 35).



**Figure 35: Input-Output diagram of GMAW Welding**

To measure the energy consumption of one unit welding process, the same setup is used as for the CNC machines.

#### **Welding consumables**

To measure the used amount of welding wire for one process unit of GMAW welding, the wire feed rate is measured and multiplied by the cycle time. Another consumable used is the shielding gas, a mixture of 75% Argon and 25% CO<sub>2</sub>, which is used to protect the weld from oxygen and ensure a high quality weld. By multiplying the flowrate with the cycle time the amount of consumed shielding gas can be calculated.

### **3.2.3. Data collection of painting process**

The product is painted with a paint spray gun which uses compressed air to spread the lacquer on the component. To calculate the amount of lacquer that is used for one process unit, the paint jar attached to the paint gun is filled up with paint and the weight is measured on a scale, then the product is painted and after that the jar gets weighed again. In order to avoid inaccuracies this process is repeated five times and an average consumption is calculated.

### **3.3. Selecting Appropriate LCA Software**

As mentioned in Chapter 2, there is different software available for LCA. Although they all fulfill the purpose of supporting the user to conduct a Life Cycle Assessment, they differ in price and optional functions. This comparison includes the educational versions of Umberto NXT LCA, GaBi and the full version of openLCA. Collecting data to conduct an LCA can be very time consuming and expensive, so it is helpful to access generic data to fill in data gap. Data may be collected and transferred to the software manually or automatically imported from a database via an interface. In such databases are independent from the LCA-Software and have to be integrated into the software. LCA data are based on product and elementary flows, which are related to environmental effects in the form of emissions. These flows are often multiple linked to additional data sets such as inputs and outputs for energy supply, transport, chemicals, materials and manufacturing processes. Some data bases are available for free, while others have to be bought. The most important free available

LCA databases are: the European Reference Life Cycle Database (ELCD), the National Renewable Energy Laboratory Data Base (NREL) and the New Energy Externalities Developments for Sustainability (NEEDS). One of the world's leading commercial databases is the Ecoinvent Database. Ecoinvent includes more than 9000 generic data sets.

In the following chapter, three of the most common LCA software tools (OpenLCA, GaBi, Umberto NXT LCA) will be presented and evaluated by the following criteria:

- Availability of free or educational licenses (1): Costs can often be the first burden for small companies when trying new methods. Moreover, since the intention is to use this software for research purposes an educational option is useful.
- Includes extensive database (2): As mentioned in Chapter 2, data collection can be difficult and very time consuming. Existing databases that include generic data such as emissions to air due to the production of electricity can fill in gaps where collecting data is impossible or very time consuming.
- Easy import of databases (3): Some software tools do not include database from the beginning, however they have the option to import external databases.
- User friendliness and flexibility (4): LCA tools should have a user friendly interface that is comparable to common software such as Microsoft Office. The amount of time to learn how to use the software should be appropriate to the results you can achieve with this software.



- Transparency (5): LCA calculations should be transparent for the user to track down each result in order to find mistakes.

Each tool is tested by working through available tutorials and on a custom product.

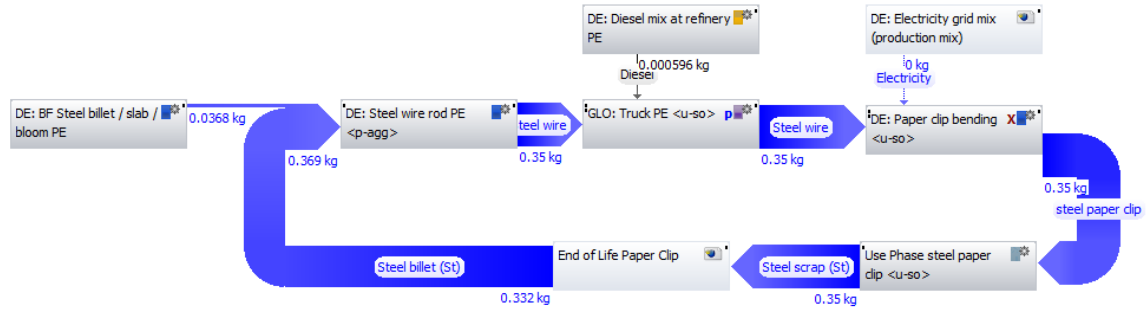
Then, based on the criteria above, each software is evaluated.

## **GaBi**

GaBi was developed by PE International. A trial version is available for free but can only be used for 30 days. Furthermore, it only includes a “test” database that is not based on real measurement or calculations. The price for the full version is about \$1000 and has to be paid on an annual basis(1). Besides that, an educational version is available that allows students and universities to use an educational version of GaBi for free. This version includes a smaller version of GaBi's own database, which makes an import of an external database unnecessary (2,3).

Before developing the first product system, the GaBi database has to be activated and a project plan has to be created. On this plan object from the database can be pasted and connected with arrows. A search function helps to find the right process easily. In addition, custom processes can be created. Therefore, all materials used have to be identified manually. Different processes are connected with each other by product or waste flows. The available tutorial of a paper clip helps new users get started (see Figure 36). In addition, there are video tutorials available that explain step by step how to use the software. While the design of the main interface is very user friendly, adding new processes and connecting them can be complicated and time consuming (4). The main reason for this is that the program does not tolerate small mistakes. Whenever user individual processes or materials are created the limited

database for raw material becomes critical. For example, in order to create a customized paint, the all specific components have to grouped and defined as paint.



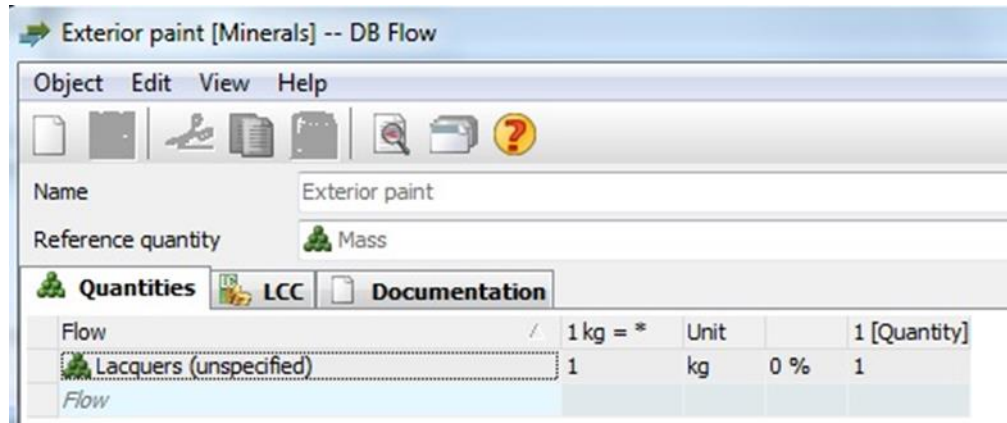
**Figure 36: Screenshot GaBi paper clip tutorial**

However, a lot of those specific components cannot be found in the included database, which leaves the user no other option than using a standard paint with different components (see Figure 37).

Nation	Name	Type / Shk	QA	Source	Object group	Last change
<b>Flows</b>						
	Paint (dispersion paint)		✓		Minerals	10/31/2012 6:00:00 PM
	Paint (silicat dispersion paint)		✓		Minerals	10/31/2012 6:00:00 PM
	Exterior paint		✓		Minerals	10/31/2012 6:00:00 PM
	Paint		✓		Materials from renew	10/31/2012 6:00:00 PM

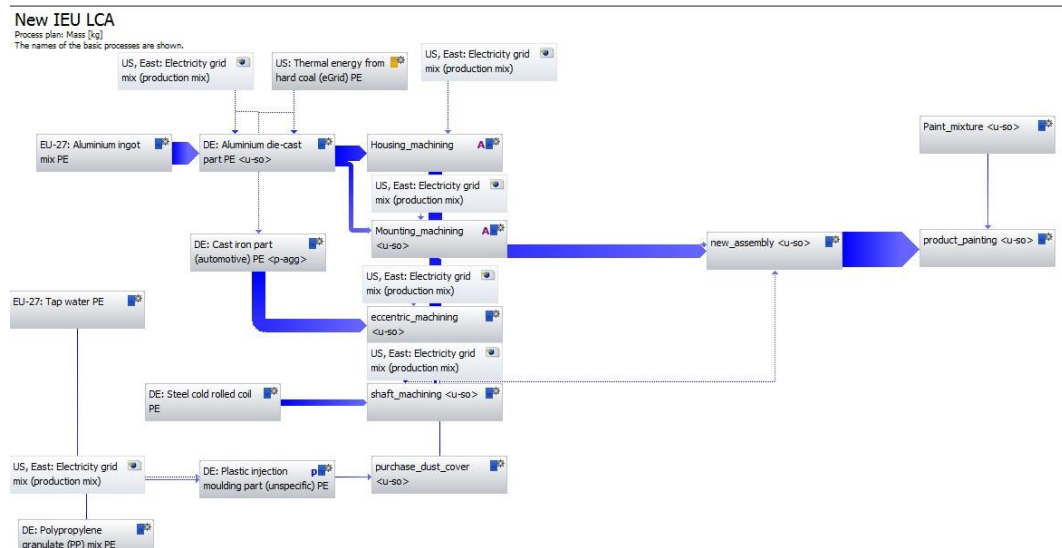
**Figure 37: Screenshot from the GaBi database for paint**

When generic data is chosen it should always be compared to the actual material or process for which it is being substituted. If “Exterior paint” is chosen in the GaBi software, more detailed information about the ingredient of the paint is missing. The detailed view for this generic paint only show one ingredient: lacquer (see Figure 38).



**Figure 38: Screenshot of the detailed view in GaBi**

Selecting a generic data set that does not fit the actual process or material that is assessed can change the environmental impact during the LCA calculations significantly. Within this research the painting process is crucial. Hence GaBi is not suitable for this research and the development of a current state model based on the case study could not be finished. A basic model of the case study developed in GaBi is shown in Figure 39.



**Figure 39: Screenshot of the current state model in GaBi**

Similar problems were identified by creating specific cutting fluids. With the use of a larger database such asecoinvent or the full version of GaBis own database, this problem could possibly be solved.

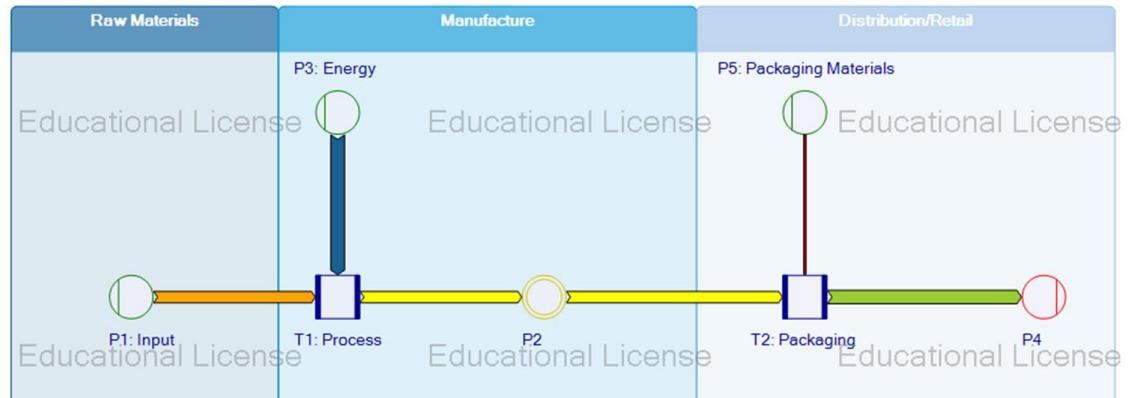
### **OpenLCA**

In contrast to the two other tools, openLCA is open source software by Green Delta. Therefore, the software is completely cost free and the full version can be used without any limitations (1). In contrast to other software solutions, openLCA includes neither LCIA methods nor inventory data within a database. The user receives an empty software tool, which then can be adjusted individually and combined with external inventory data (2). Every time, when the software starts, the user has to import and activate a database that is wanted for use. Free databases are available online e.g the European reference Life Cycle Database (ELCD) or the US LCI database. However, only one data base can be used at the same time (3). To model a system of different processes material flows have to be connected by inputs and outputs. Before the results for the LCA can be calculated LCIA and normalization methods have to be imported. Before the first system can be created, several attempts had to be made to import a database to into the software. Unfortunately, a lot of the databases recommended by Green Delta are only focused on agriculture or renewable energy. The only general database that includes processes and materials used in manufacturing is the ELCD database. OpenLCA supports new users with different types of video tutorials that help the user to setup the software and to develop his own product system (4). When this software is compared to competing software, it is less user friendly since all data input has to be done by the user. Furthermore, to setup a

product system there is no visualization of the stream, which can easily confuse the user.

### **Umberto NXT LCA**

Umberto NXT LCA was developed by a University in Hamburg, Germany. The software is often used by Universities and consulting firms. A trial version is available for free but can only be used for 30 days. There are different licenses available for Umberto that have to be bought on a yearly basis. An entry-level version starts at around \$2,000 including the ecoinvent-DB v3 database (1). This database has over 10,000 entries, making it the largest and most extensive database available. Optionally, the GaBi-DB can be purchased and integrated as well (2). Other databases such as ELCD are not implementable (3). To start using the software, there are different tutorials available that help the user understanding the software. The interface is designed to be user friendly. Developing a product system including the LCI can be done by simply drag-and-drop operations from different folder of the project explorer (4). Squares or circles that symbolize processes or input and outputs can be connected on a plan. The system, is then is presented as a petri net. In addition the different processes can be dragged into different life cycle phases (see Figure 40).



**Figure 40: Screenshot of Umberto NXT LCA Tutorial**

A special feature of Umberto is the existing preconfigured complex process that allows the user to track on an elementary flow level. This becomes really helpful when logistic or electricity generation has to be modeled. Those preconfigured processes are based on average data from different regions of the world and can be different from the actual material flow. Generic data for paint or metal working fluid shows all ingredients and byproducts that occur in the process. This way, the user can compare the generic data and verify that it fits the requirements and is similar to the actual process. However, Umberto points out that generic data should only be used when it is the processes or materials are not in the focus of the LCA study. In the case study the used paint and metal working fluid are crucial. Therefore, customized processes have to be generated. This can be done in Umberto NXT LCA by adding all known ingredients to an empty process.

The calculation of LCIA is transparent and results can be connected to different life cycle phases (5). This feature makes it easier for the user to identify environmental impacts and match them to the different phases. Umberto includes a large variety of indicators from which the user can choose from. In the educational version of

Umberto NXT LCA only three indicators can be chosen at the same time. Furthermore, the following limitations are set for the educational license:

- 25 User Defined Materials
- 25 User Defined Processes
- 3 Subnets

During the tutorials and customized projects, none of these limitations were found as critical.

## Results

After each of the LCA software was tested and evaluated according to the criteria, the results presented in Table 10 show that the Umberto NXT LCA fits all of the criteria. The only downside is that there is no free version of the software available.

**Table 10: Result of Evaluation of Different LCA Software**

Criteria	Open LCA v. 1.4.1	GaBi 6	Umberto NXT LCA
1. Free or Educational License Available	●	●	◐
2. Includes extensive Database	○	◐	●
3. Easy import of databases	●	●	●
4. User friendliness and flexibility	◐	◐	●
5. Transparency	●	●	●

○ Fulfills not the requirement    ◐ Fulfills the requirements with reservations    ● Fulfills the requirements

The educational license that was used during this research was sponsored by the Institute of Machine Tools and Production Technology at the University of Braunschweig. The biggest advantage of Umberto NXT LCA regarding this study is

that the included ecoinvent database provided a large variety of generic data, while other software include a smaller database or no database at all.

### **3.4.Selecting CACE Software**

As mentioned in Chapter 2, CACE software can help to estimate manufacturing costs, which becomes necessary when no real cost measurement is available. This can be the case when changes in the design of the product or the manufacturing processes are made. By including CACE software in this framework, costs can be estimated and compared with the environmental impact whenever there is no real cost data available. Based on the case study, basic requirements for CACE software can be derived. This section compares the aPriori, Concurrent Costing 2.3 and Siemens Pro Calc as examples of CACE software and evaluates their suitability for this research.

For the evaluation five criteria are determined in order to select software that allows the most accurate simulation of case study. To derive accurate results the individual adaption of the manufacturing steps is very important. An import from 3D CAD data makes the cost analysis easier, since geometric data is available and no manual entry is needed. For the purpose of this research it is important that the CACE software includes the calculation of the needed inventory material. Furthermore, the calculation of cycle times is important, since the cycle time is essential to calculate labor costs. As the last criterion, it is important that the software is easy to use and supports the user during the optimization process. This means, that the software supports the user during the selection of material and assists to discover weaknesses in the process. If a criterion satisfied to the full extent, the software is rewarded with a



full point. If, however, software meets a criterion only to limited extent, it is rewarded with half a point. If a does not meet a criterion at all, it is rewarded with zero points.

Criteria	Concurrent Costing 2.3	aPriori	Siemens Pro Calc
1. Manufacturing processes adjustable	●	●	◐
2. 3D-CAD data import	○	●	◐
3. Calculation of material inventory	●	●	●
4. Calculation of cycle times	◐	●	●
5. Supportive for process optimization	◐	◐	●

○ Fulfills not the requirement    ◐ Fulfills the requirements with reservations    ● Fulfills the requirements

**Figure 41: Evaluation of different CACE software**

The results of the evaluation are shown in Figure 41. In comparison, the aPriori Software achieved the highest score. aPriori is the only software which supports the user in optimizing the production process. The user has the option to choose from these proposals and to manually adjust the process. In addition, you can search for the optimal solution by the "Let aPriori decide". Furthermore, the import of 3D CAD data provides a convenient way to take into account the geometric cost drivers of the product. Another function is the calculation of cycle time and the use of materials. In General, the use of aPriori appears to be easier compared to the competition. Gaps due to unknown process data can be filled by default values from the aPriori database in order to obtain plausible results. The software packages Siemens ProCalc and Concurrent Costing require a more detailed knowledge of the manufacturing process and the individual costs. Especially for inexperienced users estimating such figures is extremely difficult.

Subsequently, the software aPriori is chosen for this framework, since it is the only software that can estimate costs and cycle times based on generic data, when no primary data is available. From a cost perspective, the focus of this research is to determine material cost for consumables and raw materials. Furthermore, the labor costs per part are estimated. Based on this data potential savings can be evaluated.

### **3.5. Developing an Enhanced Value Stream Map**

To track sustainability within the manufacturing process, different Value Stream Maps were developed (see Section 2.4.3). One approach was done by Faulkner et al., who developed the sus-VSM that includes energy consumption, raw material usage, water consumption and the social aspect of the work environment (Faulkner and Badurdeen 2014). However, no approach includes measurements based on LCA results such as Global Warming Potential. Moreover, no approach includes costs and sustainability measurements at the same time. Therefore, the traditional Value Stream Map will be adjusted and a cost and environmental perspective added according to the indicators.

Machining Housing	
☉	
CT (s)=	110
C/O( min)=	40
Uptime (%)=	88
Material use (kg)=	3583
Waste generation (kg)=	200
Energy use (kWh)=	220
GWP (kg CO2 eq.)=	7732.93
AP (kg SO2 eq.)=	71.53
HT (kg 1.4 DCB eq.)=	2304.18
Cost (\$)=	23.86

**Figure 42: Example of the adjusted VSM**

As it can be seen in Figure 42, in the adjusted VSM, the traditional measures such as cycle time (CT), change over time (C/O) and Uptime are shown in the first box underneath. The next box includes the results of the LCA. In the last box the costs are presented.

## **CHAPTER 4: APPLYING FRAMEWORK TO A CASE STUDY**

After giving a comprehensive overview of the most prominent costs factors, environmental factors, society factors and the theoretical background was given, this chapter focuses on applying this knowledge to manufacturing processes. Therefore a case study is conducted, which will be presented in the first section. Based on this, in the following sections requirements and system boundaries are set. According to these, a concept will be developed to analyze the cost and environmental impact of the product.

### **4.1.Introduction of the Case Study: Industrial Equipment Unit**

The manufacturer of the product under consideration is located in the New England area. The company manufactures industrial equipment for material flow, efficiency and safety and has been in business for over 50 years. Depending on the environment different Industrial Equipment Units (IEU) are produced. One of the most common IEU can be seen in Figure 43.

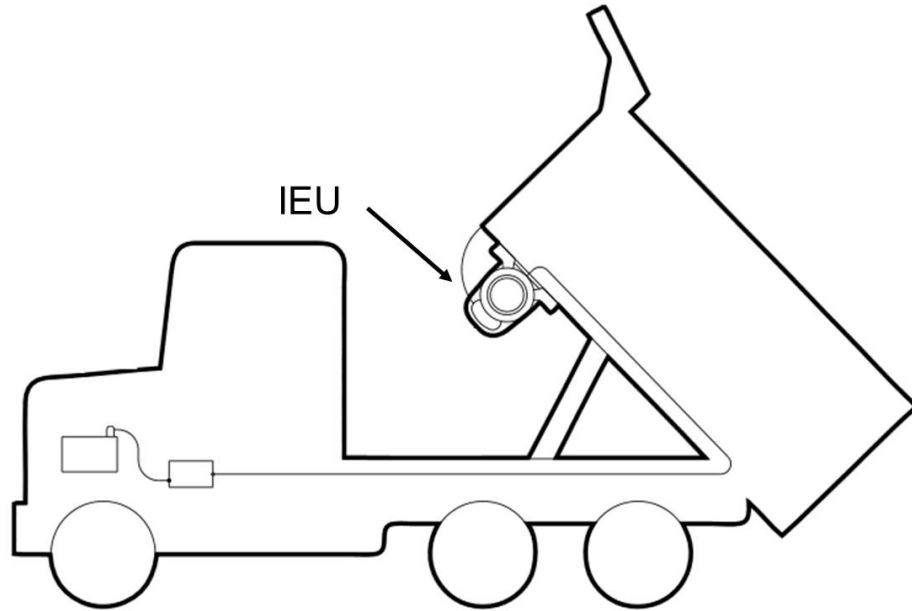


**Figure 43: Industrial Equipment Unit**

This tool shakes off materials from the inside to mobile equipment for example:

- Fertilizer spreaders and Farm equipment
- ice control and sand spreaders
- dump trucks
- concrete pumps

Therefore the device is mounted on the outside of the equipment (see Figure 44).

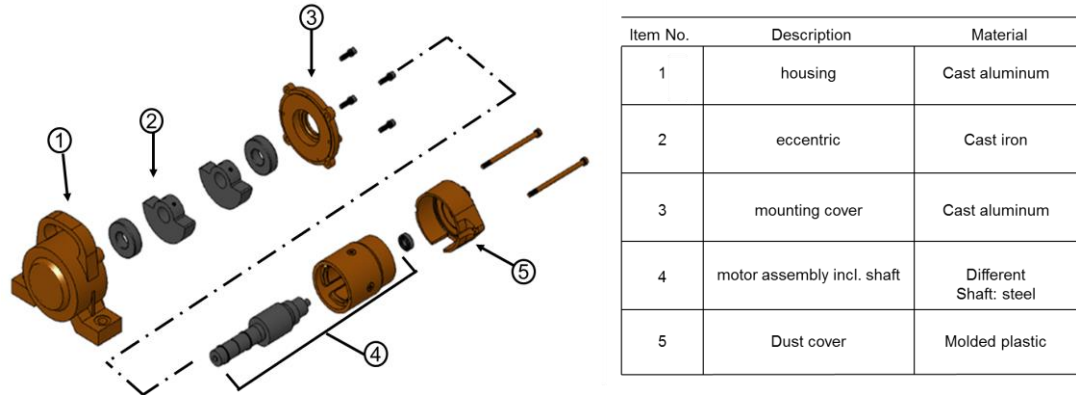


**Figure 44: IEU mounted to the body of a truck**

To get a better understanding of the main components of the product are presented.

#### **4.1.1. Main components of the product**

The main components of the IEU consist of the housing, eccentric, mounting cover, motor assembly and dust cover. Besides those main components, there are different other smaller components that are needed for the assembly. This includes screws and bearing balls (see Figure 45).

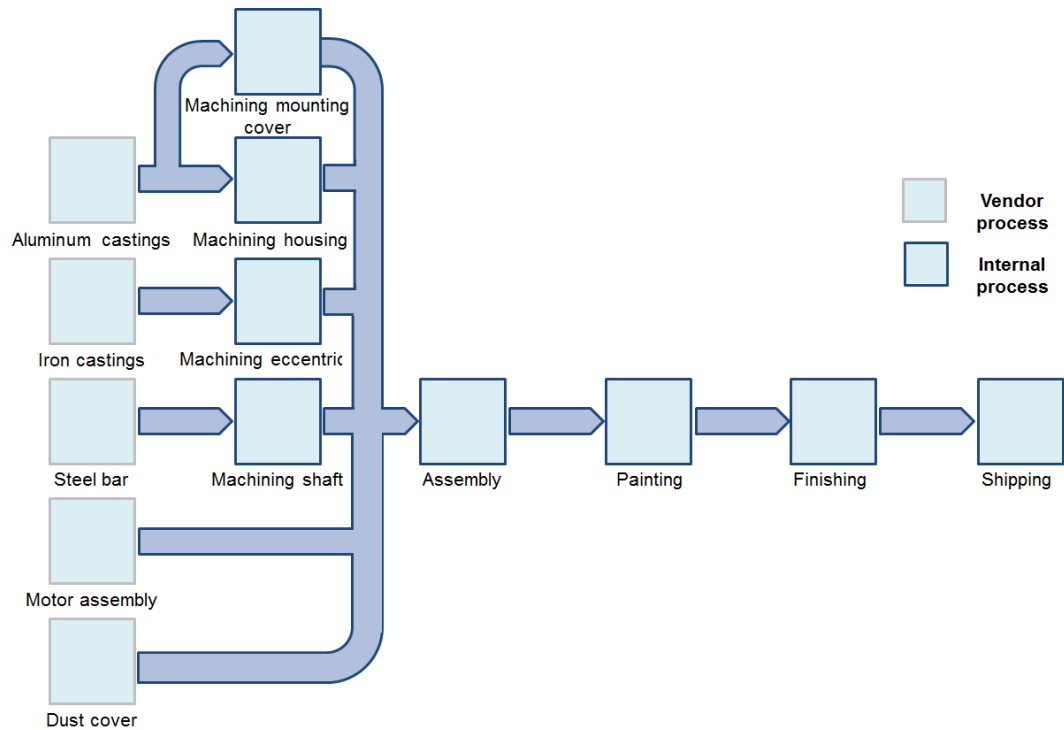


**Figure 45: Main components of the IEU**

Not all components are manufactured directly in the company itself. A lot of them are produced as blanks by a vendor and are processed further at the manufacturer.

#### **4.1.2. Manufacturing process**

After all components are produced by vendors they run through different machining processes, followed by an assembly process. After the product is assembled completely it is painted and finished (see Figure 46).



**Figure 46: simplified manufacturing process of an IEU**

The housing, eccentric and mounting cover is machined on a CNC horizontal lathe. The machine uses different tools to perform chucking, boring, turning and drilling. The machine itself is connected to a mist collector to avoid having machining fluids released into the air. During operation the tools are cooled by a continuous flow of lubrication oil. The input voltage for the machine is 220 V. Depending on the machined part and material a different setup is needed. The setup varies in tools, feed rate and cutting time. Since different jobs require different tools, tools have to be changed. The shaft is manufactured of bar stock steel and is machined on a different CNC machine. In addition, a bar feeder is used to supply the CNC machine. The machine run with 220 V input Voltage. The motor assembly is already preassembled by the vendor and can be welded to the shaft. The welding technique is MIG (GMAW) used with 75% Argon carbon-dioxide gas mixture. The plastic dust cover is



delivered ready for assembly by the vendor. The assembly process is done manually and only uses man power and different types of sealers. The next process is the painting of the complete part. The solvent based lacquer is applied with a paint spraying gun that uses compressed air. After the paint is air dried, the product gets finished and packaged for shipping.

## **4.2. Application of Life Cycle Assessment**

### **4.2.1. Goal and scope definition**

The goal of the assessment of the manufacturing process is to determine impacts of the system on the environments and humans. In that process, data has to be collected, evaluated and visualized. As a consequence, the awareness for negative effects is increased. In addition, the model can be used to create future state manufacturing processes and helps to optimize the current processes.

Three models are constructed. The first model shows the current state of the manufacturing process. The second model is an improved future state process with lower environmental impact and that provides potential cost savings. The results of both models are compared to determine the intensity of reduction of environmental impacts due to the implemented optimizations. Furthermore, there will be a differentiation in the scope of the assessment. One model will include all of the environmental impact during upstream processes such as generation of new material and resource extraction. The second model will only focus on the environmental

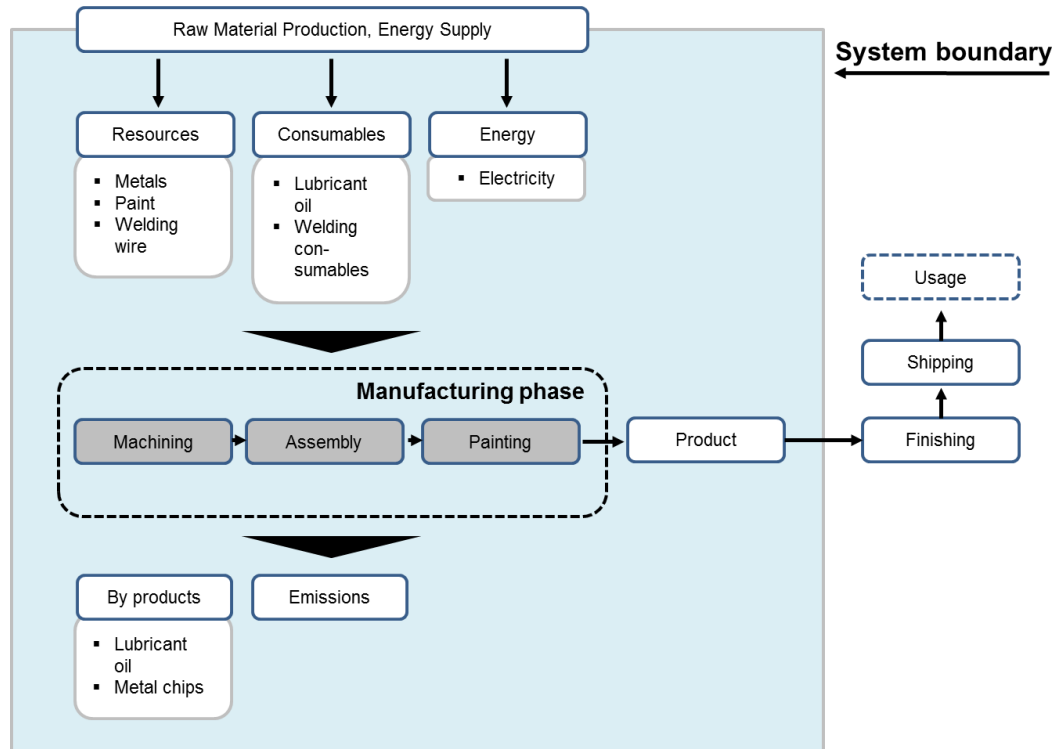
impact during the manufacturing steps within the company. According to this, the functional unit is defined.

### **Functional unit**

As explained earlier, the functional unit is used to clarify the system boundaries and the interdependence within the production system. The functional unit is defined as the manufacturing of one IEU, including all main parts. With this definition, the manufacturing process can be compared to other manufacturing processes or optimizations of the current process.

### **System boundaries**

System boundaries include several aspects. The assessment does not include the whole life cycle of the product. The first model includes the current manufacturing processes of the product within the company and all upstream processes such as raw material extraction and production of blank parts. All downstream processes such as finishing, shipping and usage are excluded. (see Figure 47).



**Figure 47: System boundaries of the analyzed product**

Another boundary is the collected data. Data is only taken into account when it is directly and exclusively related to the manufacturing of one IEU. This includes electricity, paint, raw materials, welding consumables and lubricant oil. It excludes electricity used for illumination since it cannot be tracked back to one IEU.

#### **4.2.2. Inventory analysis**

The inventory analysis and the impact assessment of both models are conducted in the software Umberto NXT LCA. Primary data is collected at the company according to the framework in section 3.2, while other data is derived from the ecoinvent database. In the following, the data collection is explained.

The input materials for this machine are blank housings, blank mounting covers (both casted aluminum) and blank eccentrics (casted iron). Before those pre-casted parts can

be assembled, they have to be machined to meet required tolerances. Therefore, different cutting tools, cutting fluid and energy are needed.

### Energy consumption

The results of the measured energy consumption are shown in Figure 48 to Figure 52. The energy demand (W) of the CNC machine A is varying through the cycle time while the energy demand of the mist collector stays constant at 5720 W. The maximum energy demand is at second 648 with a value of 9680 W. (see Figure 48). The total energy consumption of CNC machine A and the mist collector for a cycle time of 11:28 min is 1268.0 Wh.

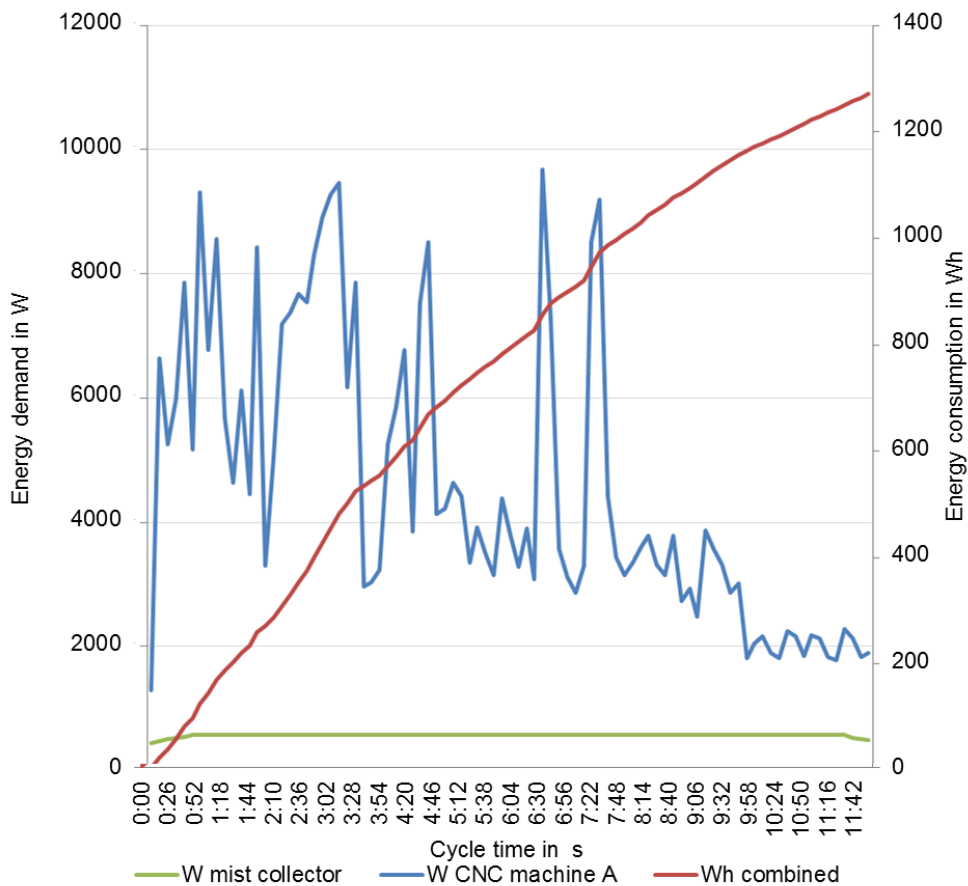
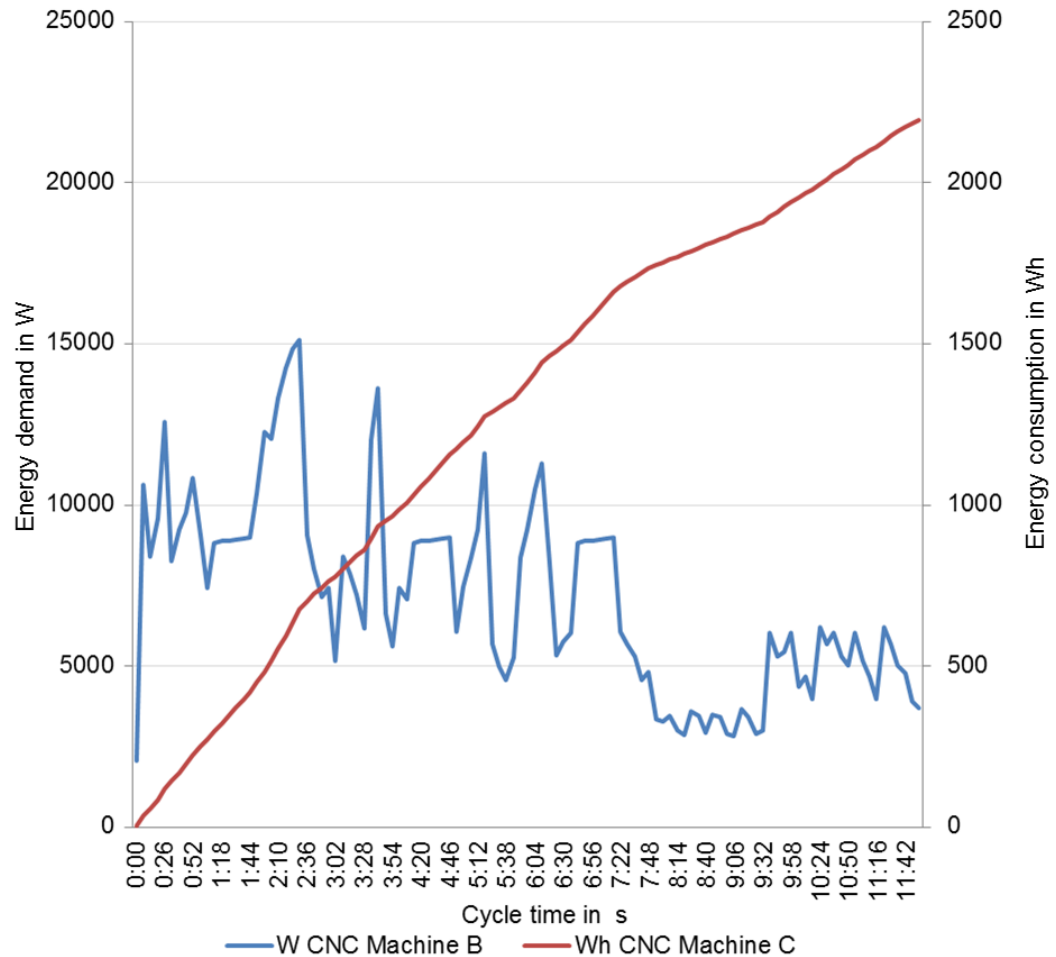
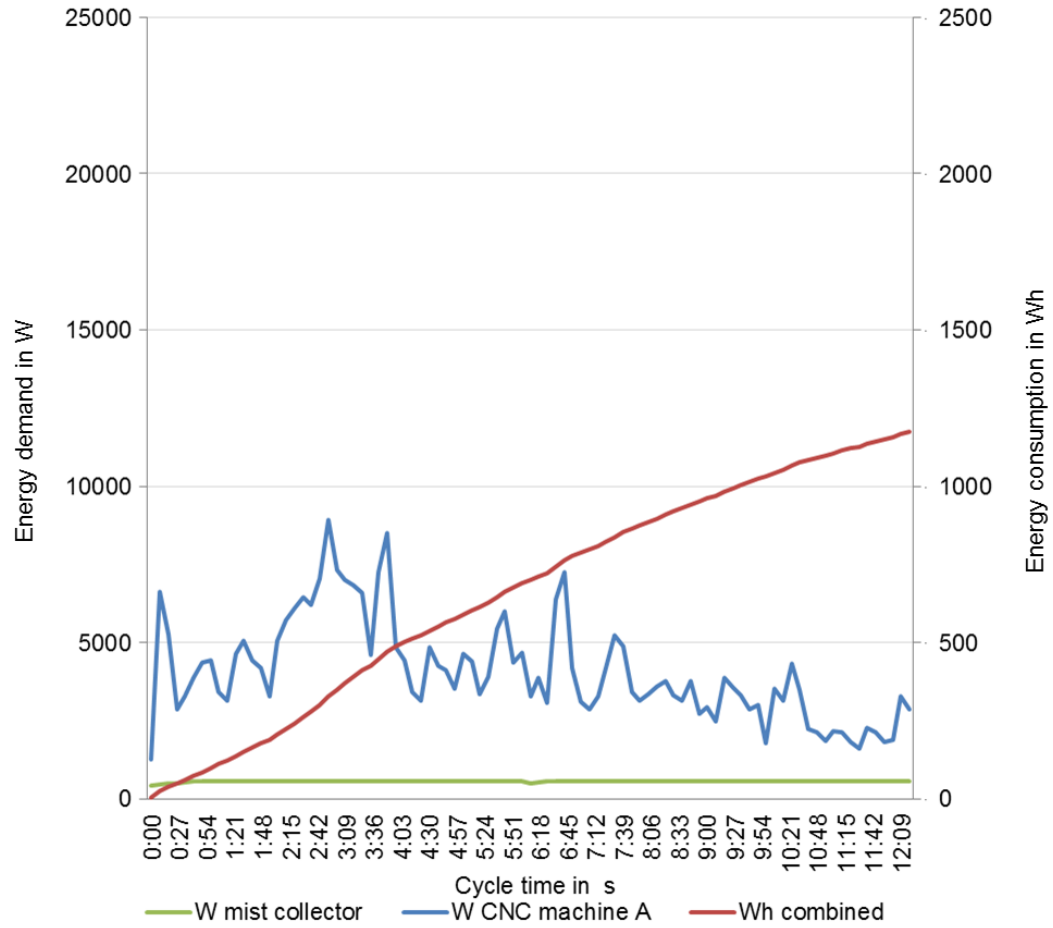


Figure 48: Energy consumption and demand for the housing on CNC A

The second machining step is done on CNC machine C which does not have an attached mist collector. The maximum energy demand is at second 23 with a value of 15,136 W (see Figure 49). The total energy consumption of CNC machine C for a cycle time of 11:50 min is 2200 Wh. Compared to CNC machine A, the minimal energy demand is higher for the CNC machine C.

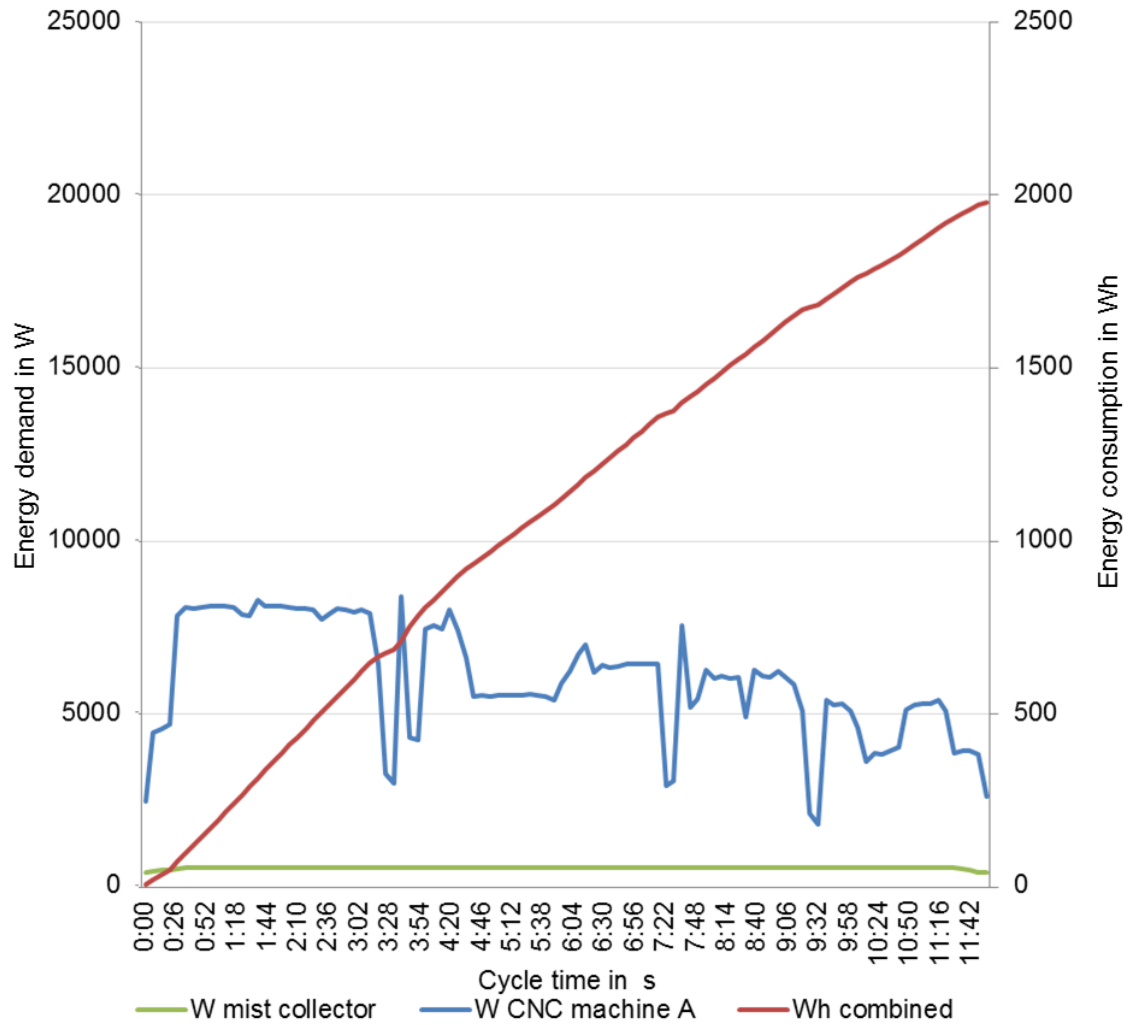


**Figure 49: Energy demand and consumption for the housing on CNC C**



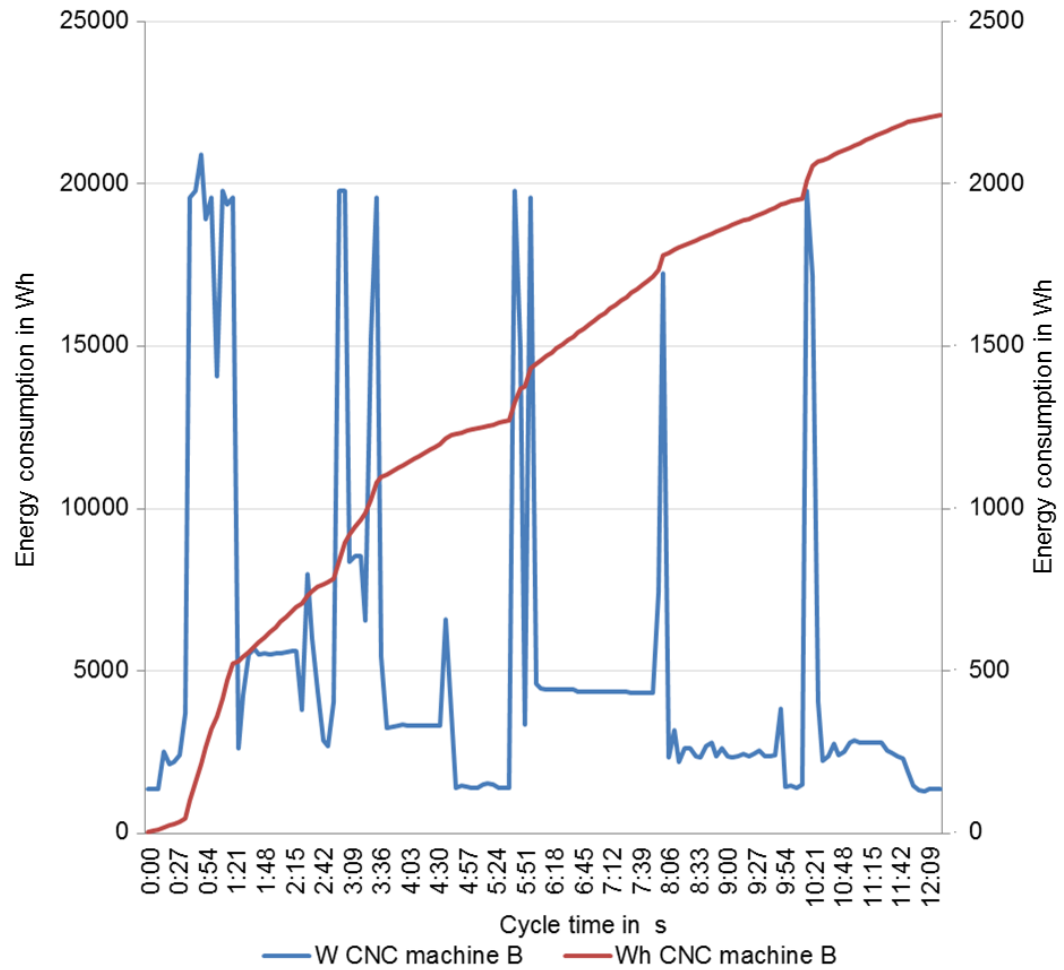
**Figure 50: Energy consumption and demand for mounting cover on CNC A**

Figure 50 shows the energy demand of CNC-machine A when manufacturing one mounting cover. The cycle time was measured with 11:30 min. The maximum energy demand is at 2:42 min with a value of 8910 W. The total energy consumption is 1160 Wh.



**Figure 51: Energy consumption and demand for eccentric on CNC A**

The cycle time to machine one eccentric is 11:45 min and requires 2000 Wh. As it can be seen in Figure 51, the highest energy demand was measured at 3:28 with a value of 8404 W. Comparing the energy profile of the eccentric with the housing and the mounting cover, the analysis shows that the average energy demand for the eccentric is higher. One reason for this might be that the eccentric is made of casted iron, while the mounting cover and housing are made of casted aluminum which is softer than iron and therefore requires less energy.



**Figure 52: Energy consumption and demand for shaft on CNC B**

The shaft is machined on CNC machine B that does not have a mist collector attached. The total cycle time for the machining process was measured with 12:29 min. The total energy consumption is 2210 Wh. Comparing the energy profile with the profiles of the housing or the eccentric, it can be seen that the peaks in the energy demand are significantly higher. One reason for this might be that the shaft is made of steel which has a higher hardness than aluminum and iron. The highest energy demand is at 0:44 min with 20900 W.



### Material usage and solid waste generation

The material usage and solid waste generation was measured according to the framework in section 3.2. An example is shown in Table 11.

**Table 11: Results of weight measuring for eccentric component**

Sample #1	Blank component weight in Kg	Machined component weight in Kg	Scrap in Kg
1	32180	29190	2980
2	33740	30330	3400
3	31950	28780	3170
4	32060	29490	2570
5	3242	2954	2880

Based on the measurements of the different samples, a mean value for each component and manufacturing process is derived. An overview of the results is given in Table 12.

**Table 12: Overview of the scrap metal production during machining**

Component	Machine	Average blank component weight in g	Average machined component weight in g	Average scrap in g
Housing	CNC A	38520	35830	2690
Housing	CNC C	35830	33830	2000
Mounting cover	CNC A	17780	15040	2740
Eccentric	CNC A	32200	29190	3010
Shaft	CNC B	24940	16130	8810

### **Cutting fluid consumption**

In this case study the CNC machines use a 197 L (52 gallon) tank for cutting fluid. It is assumed that each machine runs 40 hours per week. Furthermore, it is assumed that the cutting fluid has to be replaced every four weeks. Based on the finding of Clarens et al. following effective loss of cutting fluid can be derived for this case study (see EQ.3).

$$\frac{197 L}{40 \text{ hours} * 4 \text{ weeks}} = 1.231 \frac{L}{h} = 0.205 \frac{L}{min} \quad (\text{EQ. 3})$$

This operating figure can be used to calculate the loss of cutting fluid for every component by multiplying it with the cycle time. The results are presented in Table 13.

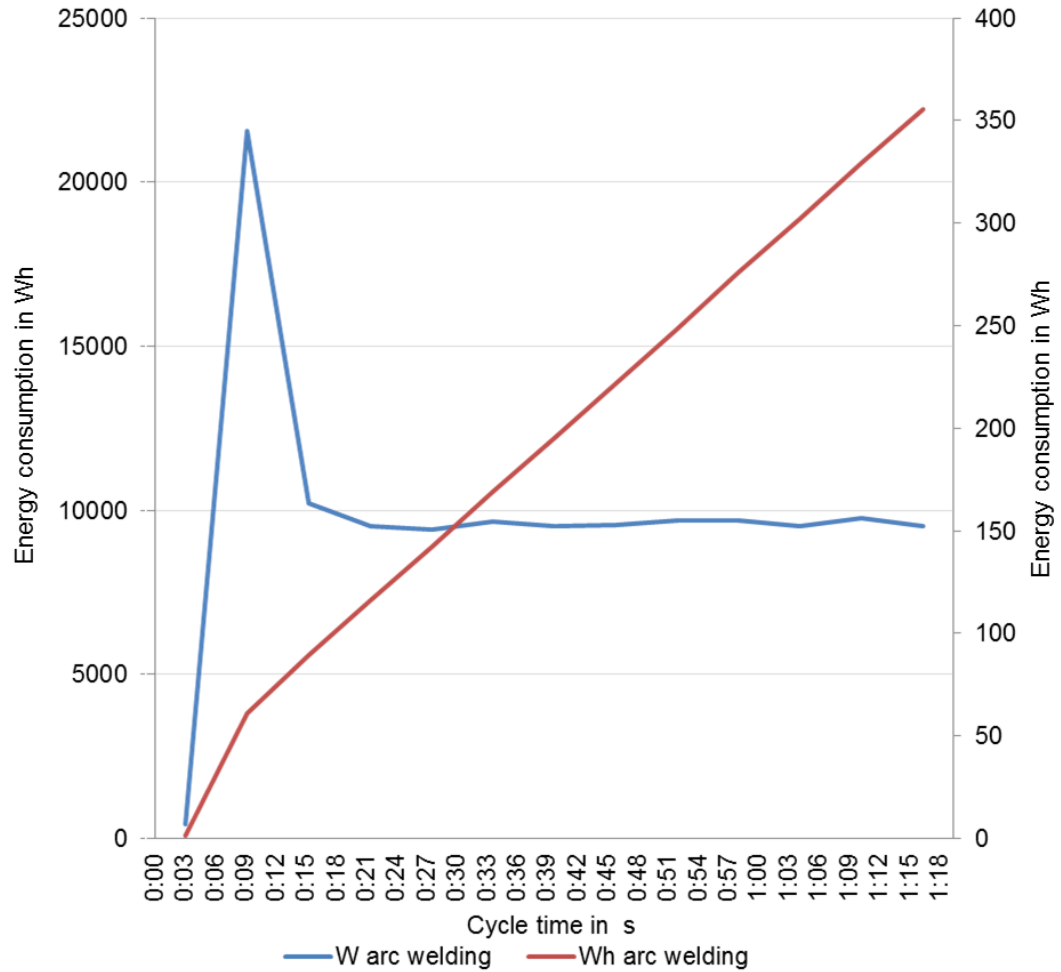
**Table 13: Collected data for CNC machines**

Component	Machine	Cycle time in min	Energy consumption in Wh	Produced Scrap In g	Used cutting fluid in L
Housing	CNC A	11:28	1260	2690	2.35
Housing	CNC C	11:50	2200	2000	2.419
Mounting cover	CNC A	11:30	1180	2740	2.35
Eccentric	CNC A	11:45	1980	3010	2.408
Shaft	CNC B	12:29	2210	8810	2.56

After all data for the machining processes are gathered, in the next step the welding process will be analyzed.

#### **Data collection for welding**

In this case study GMAW welding is used to weld the manufactured shaft to the rotor as part of the motor assembly. The cycle time was measured with 1:28 seconds which leads to a total energy consumption of 350 Wh (see Figure 53).



**Figure 53: Energy consumption welding one shaft**

The feed rate for the welding wire was measured as 1.2 m per min which leads to a consumption of 2.4m welding wire per process unit. The flowrate of the shielding gas in this case study is 14.15 Liters per minute (30 CFH). By multiplying the flowrate with the cycle time the amount of consumed shielding gas can be calculated. For each process unit 38.3 Liter of shielding gas is required.

**Data collection of painting process**

After all parts are manufactured and the IEU is assembled, it is painted. The paint used is a gloss metal lacquer. The list of ingredients can be seen in Table 14.

**Table 14: List of ingredients gloss metal lacquer**

Ingredient	Percentage
Isopropyl Alcohol	17
Methyl Ethyl Ketone (2-Butanone)	17
Ethylbenzene	4
1-Methoxy 2-Propanol Acetate	4
Toluene (Methyl Benzene)	37
n-Butyl Acetate	8
Xylenes (Dimethyl Benzenes)	10
Molybdated Chrome (contains lead)	3

The IEU is painted with a paint spray gun which uses compressed air to spread the lacquer on the component. An average of 1290 g of paint is used to paint one IEU.

### **4.3.Implementation of the data into LCA Software**

After the functional unit and the boundaries are explained and the necessary data is collected in the next step a LCA model of the IEU manufacturing process. This model is developed in the software Umberto NXT LCA, which was selected in Section 3.3.

In this assessment three different models are built. The first model simulates the current state of the manufacturing process. It was assumed that 10000 IEU are produced every year. The second and third models represent possible future states of

the manufacturing process. They are developed based on the results of the current state LCA. The goal is to reduce the overall environmental impact by replacing manufacturing processes which have high environmental impacts or modifying them to reduce their impact. Within the models different changes regarding single manufacturing processes are conducted. These changes are all theoretical and based on other research. However, it is not within the scope of this research to perform these changes in the actual manufacturing system. The basic construction of both models is the same as Model 1 shown in Figure 54. In the following, the current state model and the two future state models are presented.

#### **4.3.1. Model 1: Current State**

The current state model is divided into the phases: raw material, manufacture and distribution/ retail. However, the focus of the LCA is on the manufacturing phase and the upstream processes. In the first phase which is called Raw Material all raw material processes such as aluminum casting, iron casting, steel production and injection molding take place. The raw material processes are marked as light green squares. Each process needs different inputs presented as green circles and outputs presented as red circles. However, all raw material processes are modeled based on generic data as shown in Table 15. The preconfigured processes from the database are used, since it is beyond reasonable efforts to gather primary data. The blank castings used in this case study, for example, were produced in a foundry in China.

**Table 15: List of generic data used within the LCA of the IEU case study**

Material/Flow/Process	Name of Data Set	Source
Electricity	Market for electricity, medium voltage	North-East Power Council - US
WeldingArc steel	Market for welding, arc, steel [GLO]	Global Average - ecoinvent
Aluminum Casting	Casting, aluminum [GLO]	Global Average - ecoinvent
Iron Casting	Cast iron production [GLO]	Global Average - ecoinvent
Hot rolling, steel	Hot rolling, steel [GLO]	Global Average - ecoinvent
Injection Molding	Injection Molding [GLO]	Global Average - ecoinvent

To connect different processes, connections are needed which are presented as yellow circles. The outputs of the raw materials are blank components and are marked as dark green squares. In the next step all blank components are machined. All machining processes are marked as blue squares. Every machining process needs the blank component, electricity and metalworking fluid as an input. The output consists of different types of metal scrap, used metal working fluid and the machined part. The data entry for each machining process is based on the collected primary data in Section 4.2.2. Although there is generic data available for paints and metal working fluid in the data base, new materials based on the list of ingredients were created. This ensures more reliable results, since both fluids contain very specific types of chemicals that might differ from the generic data and as a result have different environmental impacts. The electricity is sent by the process Market for electricity of East North America. This dataset describes the electricity available on the medium voltage level in this regional entity of the North American Electric Reliability Corporation (NERC). This is done by showing the transmission of 1kWh electricity at medium voltage. To

weld the shaft and the rotor together, electricity, welding wire and welding gas are used as inputs. To create those inputs generic data from the database is used (see Table 15). This is admissible, since the generic data matches the characteristics of the material used in the case study. The dust cover component is made out of molded plastic and requires no further machining. It can directly be assembled after its arrival at the company. The assembly of all parts is done manually with the support of a screwdriver. In the last step the painting process is modeled. Figure 54 shows the developed model of the manufacturing process. After the model is completed, the impact assessment is conducted.

#### **4.3.2. Model 2: Coconut-oil based cutting fluid and powder coating**

The second model represents an optimized version of the IEU manufacturing process. In the optimized model, all machining processes use coconut oil based metalworking fluid instead of conventional mineral based metalworking fluid. The fluid was modeled according to the results of the research of Perera. This metalworking fluid contains water (90%), coconut oil (7%) and emulsifier (3%), which are classified as nontoxic (Perera, G. I. P. 2014). For the model it is assumed, that the same amount of fluid is needed for the machining processes as before. Furthermore, it is assumed that the change of the fluid does not change the required energy consumption during the machining process and is as durable as the mineral based metalworking fluid. Those assumption are justified based on the results of Lawal et al. 2012.



In addition the current painting process was replaced by a generic powder coating process from theecoinvent database.

### **4.3.3. Model 3: unpainted IEU**

Model 3 is based on the current state model, but does not use any type of surface finish such as lacquer or powder coating. This proposed design change is reasonable since the housing and all other parts that protect the inside of the IEU are made of aluminum and therefore are already rust-resistant. However, there could be other positive or negative effects to the functionality of the product if the surfaces are left entirely uncoated. For example, the long-term product durability could be affected. From a marketing perspective, some brand recognition could be lost if the company does not use its signature paint color on all outer components. Alternatively, the company could capitalize on the product design change by promoting a “new, environmentally friendly” uncoated alternative that lowers costs for customers and promotes their interest in environmental sustainability.

## **4.4.LCA Results**

### **4.4.1. Model 1: Current State**

The first result of the assessment is demonstrated in Figure 54. The so called Sankey diagram shows the flow of mass and energy in the supply system of model 1. Different types of flows can be selected or all flows can be selected at the same time. Every material has another color. The width of the arrows presents the dimension of the mass or energy flow.

The Sankey diagram gives first visualization of the important flows of a product system within the different life cycle phases. Hereby, extensive flows are able to be determined. In case of the IEU, the material flows for the aluminum casting in the life cycle phase for raw materials is the largest flow within the model. Since the Sankey diagram displays the arrows in proportion to all other flows and the aluminum casting is very dominant, every other flow appears to be very thin or is even hard to identify.

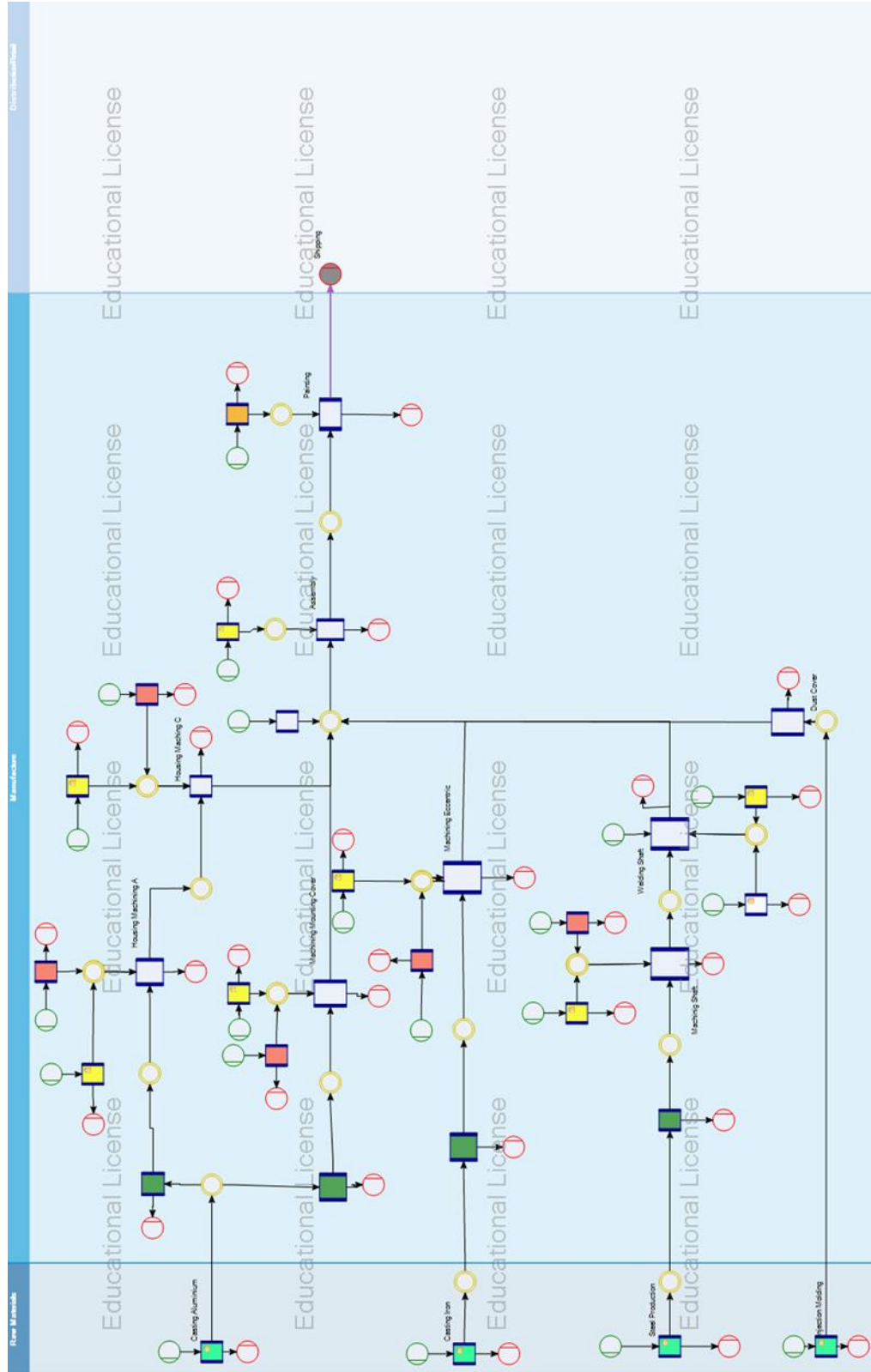
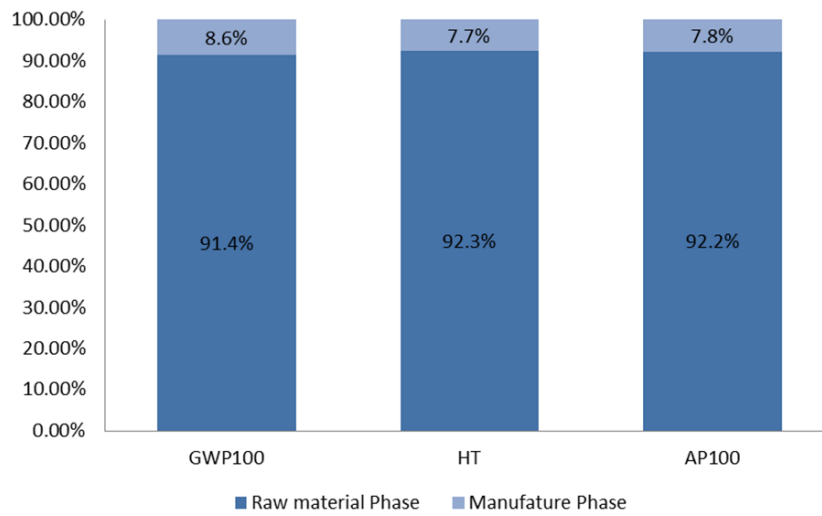


Figure 54: LCA-Model of the IEU

The next section presents the results of the ReCiPe midpoint approach. The following indicators within this method are used:

- Climate change, Global Warming Potential (GWP) 100 in kg CO<sub>2</sub> equivalent
- Human toxicity (HT) in kg 1.4-DCB equivalent
- Acidification potential (AP), AP 100 in kg SO<sub>2</sub> equivalent



Indicator	Raw Material	Manufacture
GWP100 in kg CO <sub>2</sub> -Eq	520,309	49,057
HT in kg 1.4-DCB-Eq	161,471	13,463
AP100 in kg SO <sub>2</sub> -Eq	2945	247

**Figure 55: Overall LCA results of current state model**

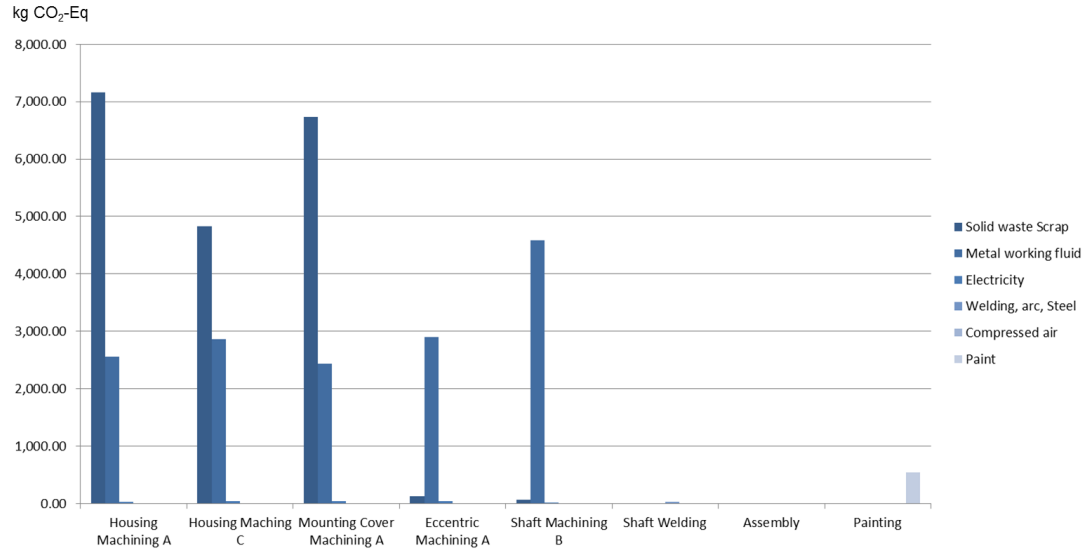
As shown in Figure 55 over 90% of the environmental impact is done during the Raw material phase of the LCA analysis. During the raw material phase, the material is extracted and the blank components are produced for the housing, mounting cover,

dust cover and shaft. However, the raw material phase can hardly be influenced by the manufacturer of IEU.

**Table 16: Quantities of used materials for each manufacturing step**

Used Input Material (in kg)	Housing Machining A	Housing Maching C	Mounting Cover Machining A	Eccentric Machining A	Shaft Machining B	Shaft welding	Painting
Used Input Material (in kg)	38,520	35,830	12,000	32200	16130	-	1,290
Solid waste Scrap (in kg)	2,690	2,000	2,740	3,010	8,810	-	-
Metal working fluid (in kg)	23,506	24,258	23,575	24,087	25,590	-	-
Electricity (in kWh)	1,260	2,200	1,180	1,980	1980	7,320	-
Welding,arc,steel (in m)	-	-	-	-	-	2,000	-
Compressed air (in m <sup>3</sup> )	-	-	-	-	-	-	370

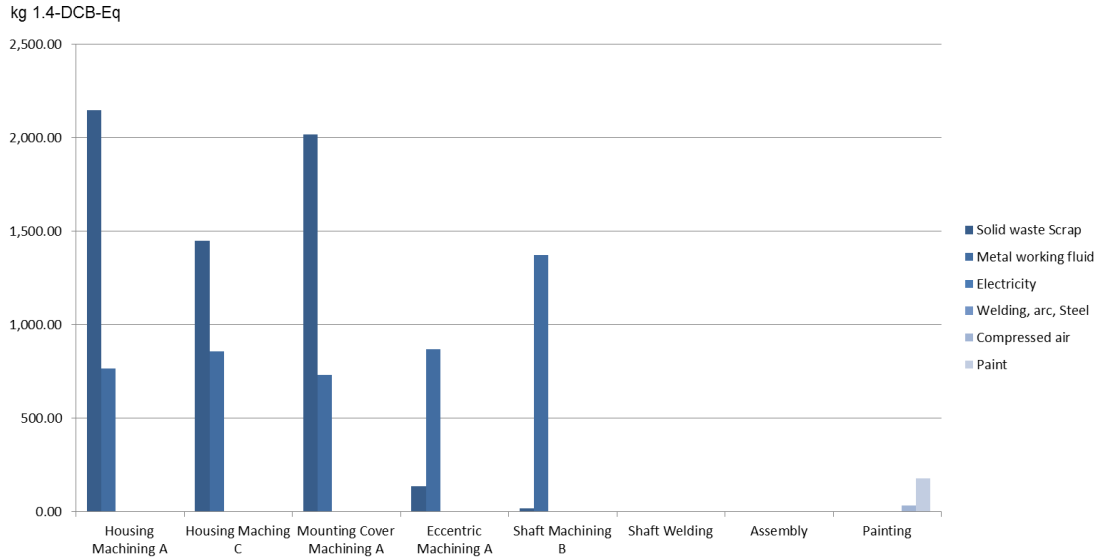
The manufacturing phase is responsible for about eight percent of the total environmental impact within the scope of this study. All manufacturing steps are performed directly in the company, so they are easier to influence and change. In the next step, the results from the manufacturing phase are presented. Therefore, every manufacturing step will be analyzed. Table 16 shows the used quantities of every manufacturing step. Raw material refers to the input of raw material such as blank parts or paint. Solid waste scrap refers to the any type of scrap that is produced during the manufacturing step. These quantities are the basis of the following results.



**Figure 56: GWP100 of Model 1 split up by manufacturing steps**

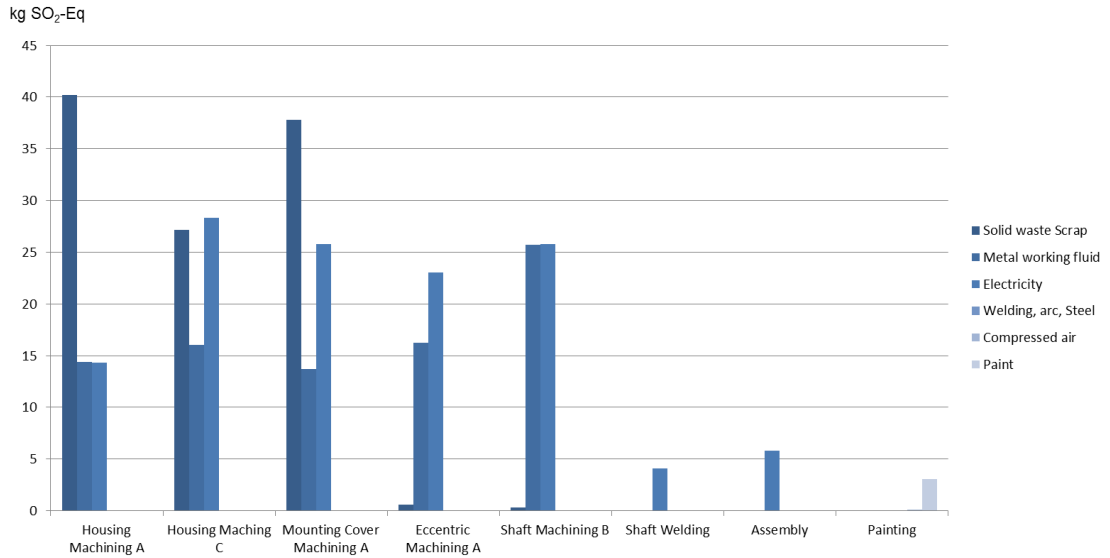
Between 60 – 70% of the Global Warming Potential (GWP) is related to CO<sub>2</sub>-emissions caused by aluminum scrap metal that is wasted within the machining phase. The second biggest contributor of CO<sub>2</sub>-emissions is the used Metal working fluid, followed by paint. Comparing the aluminum components (Housing and Mounting Cover) with the eccentric or which, which are made of iron and steel, it can be seen that the amount of released CO<sub>2</sub>-emissions is significantly lower (see Figure 56).

Next, Figure 57 presents the results of the human toxicity indicator in 1.4-DCB equivalents. The highest environmental impact according to this indicator is related to the generated aluminum scrap.



**Figure 57: Human toxicity of Model 1 split up by manufacturing steps**

The acidification potential for each manufacturing step measured in kg sulfur dioxide equivalents is shown in Figure 58. The generated aluminum scrap is the highest contributor for acidification with a maximum of 40 kg SO<sub>2</sub>-equivalents for the first machining process of the Housing. In contrast to the other indicators, the used energy has a much higher impact on the acidification potential of each manufacturing process.



**Figure 58: AP of Model 1 split up by manufacturing steps**

The results of the current state model reveal that the solid waste scrap, metal working fluid and paint are the biggest contributors of environmental impact within the manufacturing of an IEU. The second model replaces the used metalworking fluid with a coconut oil based fluid and uses powder coating instead of paint. The results of the LCA are presented in the following second model.

#### **4.4.2. Model 2: Coconut-oil based cutting fluid and powder coating**

The results of the midpoint approach are shown in Figure 59 and Figure 60. Since all improvements are performed within the manufacture phase, the all indicators in the

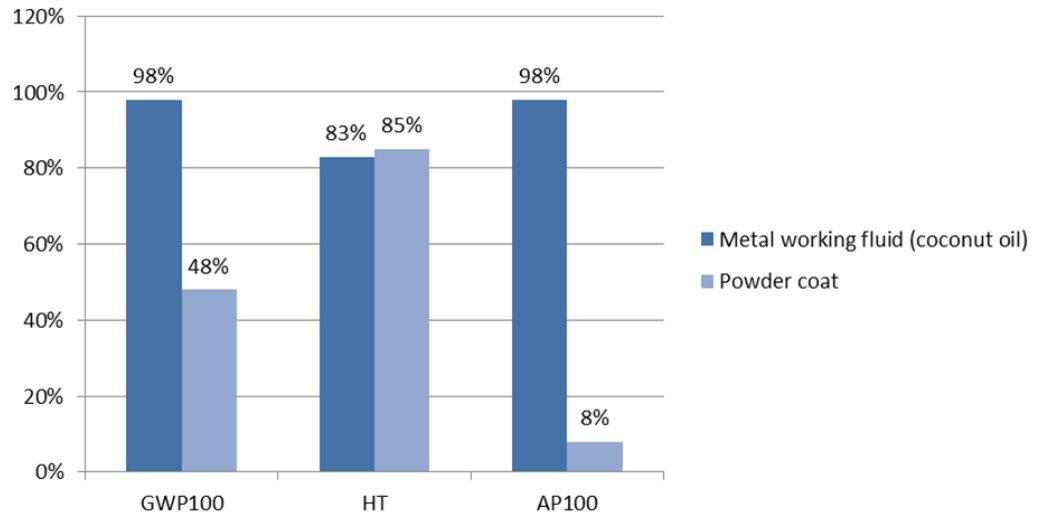


raw material phase are equal to Model 1, while they are significantly lower during the manufacture phase (see Figure 59).

Indicator	Raw Material	Manufacture
GWP100 in kg CO2-Eq	520309.2	19,743.68
HT in kg 1.4-DCB-Eq	161472	5,944.38
AP100 in kg SO2-Eq	2945.133	237.902

**Figure 59: Overview of environmental impact of Model 2**

This improvement is achieved by the replaced metalworking fluid on coconut oil bases and using powder coating instead of spray paint. As shown in Figure 60, there is a significant potential for improvement.



	GWP100 in kg CO2 Eq	HT in kg SO2-Eq	AP100 in kg 1.4 DCB-Eq
Metal working fluid	15,337.00	918.45	86.08
Metal working fluid (coconut oil)	287.11	153.27	1.67
<b>Potential improvement</b>	<b>15,049.89</b>	<b>765.18</b>	<b>84.41</b>
Paint	544.62	178.55	3.08
Powder coat	284.50	26.02	2.83
<b>Potential improvement</b>	<b>260.12</b>	<b>152.53</b>	<b>0.25</b>

**Figure 60: Potential improvements in the manufacturing phase of Model 2**

Due to the change of metal working fluid 15,049.89 kg of CO<sub>2</sub>-equivalent emissions can be avoided, which is 98% of the released emissions due to the metal working fluid used currently. The human toxicity can be decreased by 83%. In addition, the acidification potential can be decreased by 98% as well. By using powder coating, the global warming potential can be decreased by 48%. Furthermore, the human toxicity can be decreased 85% while the acidification potential can be decreased by 8%.

#### 4.4.3. Model 3: No paint

Model 3 is based on the current state model but does not include the painting process. Therefore, the impacts during the raw material phase are the same as in Model 1. In Figure 61 the potential improvement for model 3 is shown. Compared to Model 1 544.62 kg of CO<sub>2</sub>-equivalent, 178.55 kg of SO<sub>2</sub>-equivalent and 3.08 kg of 1.4 DCB-equivalent can be saved.

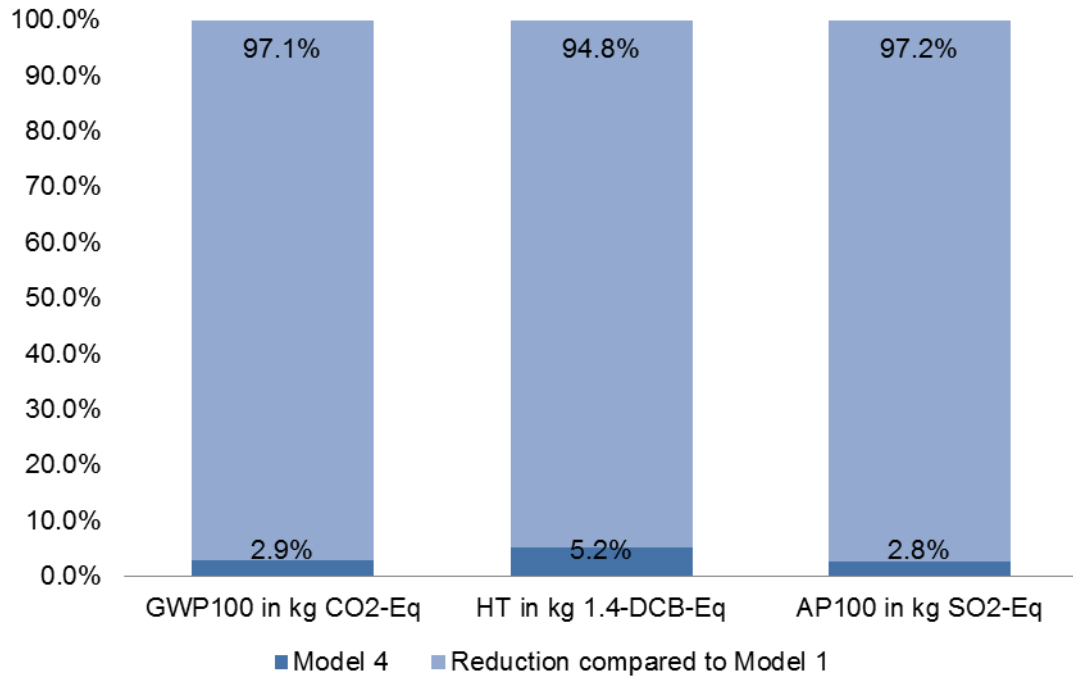
	GWP100 in kg CO2 Eq	HT in kg SO2-Eq	AP100 in kg 1.4 DCB-Eq
Paint (Model 1)	544.62	178.55	3.08
Powder coat (Model 2)	284.50	26.02	2.83
No paint (Model 3)	0.00	0.00	0.00

**Figure 61: Comparison of the impact improvement by changing the painting process**

Overall, the effect of the optimization of model 2 and 3 are smaller than expected. The analysis of the models with the midpoint approach showed that only 10% of the environmental impact is done during the Manufacture phase. This environmental impact was reduced significantly by changing the metal working fluid and the paint of the IEU. The emissions that cause global warming were reduced by 60%, the human toxicity was reduced by 55% and the acidification was reduced by 4%. This reduction of impacts is small compared to the overall environmental impact and results into an overall reduction of emissions of 5%. Further research should concentrate on determining more effective options in all life cycle phases. Therefore, two additional models are developed which focus on the raw material phase of the IEU.

#### **4.4.4. Further Future State Models**

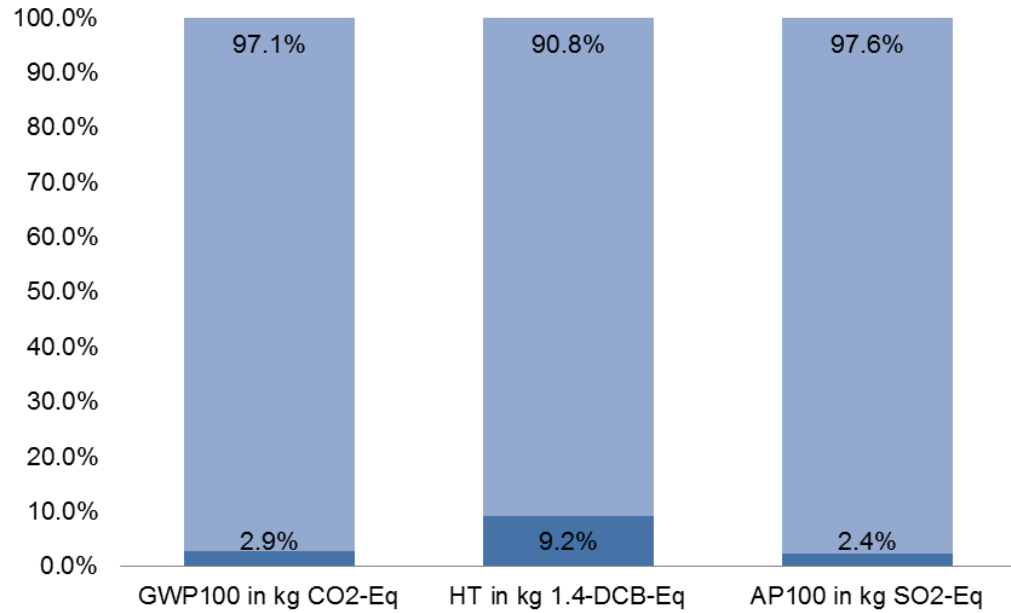
In addition to the three future state models above, two other models are developed. Model 4 is based on the assumption that the housing and mounting cover is made of plastic. Model 5 is based on the assumption that the housing and mounting cover is made of cast iron. Models 4 and 5 focus on reducing the impact that is caused by the raw material phase of the production system which has not been included in the earlier future state models. This is important because the production of the blank aluminum castings that are used for the housing and the mounting cover have a high impact. The processes could be optimized in a new model but in reality the manufacturer of the IEU has no influence on the external processes. However, it might be possible to change the material from aluminum to iron casting or even plastic, which would decrease the environmental impact significantly. Furthermore it was assumed that the amount of material used will not change.



Model	GWP100 in kg CO2-Eq	HT in kg 1.4-DCB-Eq	AP100 in kg SO2-Eq
Model 1	569,367	174,936	3,193
Model 4	16,338	9,168	88
<b>Reduced Impact</b>	<b>553,028</b>	<b>165,768</b>	<b>3,105</b>

**Figure 62: Comparison of Model 1 and Model 4 (Plastic)**

An overview of the impact based on generic data is given in Figure 62 and Figure 63. As a result of the changes in in model 4, the overall GWP100 could be decreased by about 97%, the HT by 94.8% and the AP100 by 97.2% (see Figure 62). The overall impact reduction of model 5 in comparison to the current state model can be seen in Figure 63. Similar to model 4, there is a significant improvement for all three indicators. The GWP can be reduced by 97.1%, the HT can be reduced by 90.8% and the AP can be reduced by 97.6%.



Model	GWP100 in kg CO2-Eq	HT in kg 1.4-DCB-Eq	AP100 in kg SO2-Eq
Model 1	569,367	174,936	3,193
Model 5	16,315	16,176	78
<b>Reduced Impact</b>	<b>553,052</b>	<b>158,760</b>	<b>3,115</b>

**Figure 63: Comparison of Model 1 and Model 5 (Cast Iron)**

Model 4 and model 5 are optimistic regarding the environment the IEU is used in. Moreover, there was no primary data available to conduct a more detailed LCA, which requires further research.

#### **4.5. Cost Aspect**

After it is shown that the suggested optimizations lead to a reduced environmental impact of the production the next section analyzes how those optimizations influence the costs of product. The costs are derived directly from the manufacturer of the IEU or are estimated based on other case studies.

#### 4.5.1. Costing: Painting

The type paint that is used in the current state model is priced with \$210.37 per 18.92 L (5 Gallon). Furthermore the cost of labor is estimated with \$127.78 per hour. The cycle time of the painting process was measured with 10:47 min. This leads to costs for painting one IEU unit of \$37.29 including material costs and labor. To calculate the cost for powder coating, aP priori software was used to estimate the costs. This estimate does not include investment costs for new machinery. According to aP priori, the cycle time for powder coating one IEU is 10:14 min and the material costs can be estimated with \$6.70. This leads to \$28.49 per IEU including labor and material, which means potential saving of \$48.75 per IEU. Comparing Model 3, which uses no type of paint, with Model 1, has the highest saving potential of \$37.29 per IEU (see Figure 64).

Model	Type of coating	Cycle time in s	Labor cost In \$	Material Cost in \$	Total cost in \$	Savings in \$
Model 1	Paint	10:47	22.96	54.28	77.24	0
Model 2	Powder coat	10:14	21.79	6.70	28.49	48.75
Model 3	No paint	0:00	0.00	0.00	0.00	77.24

**Figure 64: Costs and potential savings for coating processes**

By summing up the savings for an annual production of 10000 IEU between \$284,935 and \$772,403 can be saved depending on which model is used.

#### 4.5.2. Costing: Metalworking Fluid

The metalworking fluid used in the current state model is produced by Castrol and is priced with \$1,035 and is available in drums of 208L (55 Gallons). The cost per liter of used metalworking fluid is \$4.97. However, this does not include the costs that are associated with the disposal of the cutting fluid. To compare it with the coconut-oil based metalworking fluid, the cost has to be estimated. The metalworking fluid contains 7% of coconut oil, 3% of Span 80 (emulsifier) and 90% of water (Perera, G. I. P. 2014). The Coconut oil is estimated with \$726 per drum of 208L. The price for the emulsifier is estimated with \$520 per drum of 208L. The cost for the used water is negligible. Based on this estimates the cost per one liter of coconut oil based metal fluid is \$0.30. Figure 65 compares the two metalworking fluids on a per part basis. By replacing the metalworking fluid about \$56.52 can be saved per part. For the annual production of 10000 IEU this means potential savings of \$565,155.

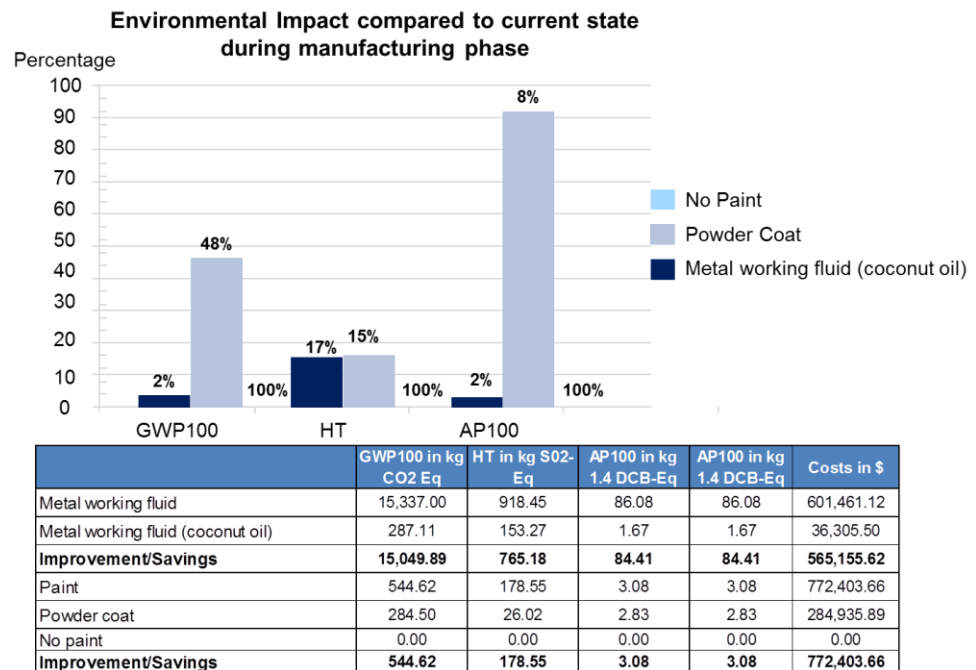
Component	Machine	Cycle time in s	Used metal working fluid in L	Costs for current fluid in \$	Costs for coconut oil based fluid in \$	Savings in \$
Housing	CNC A	11:28	2.35	11.68	0.71	10.98
Housing	CNC C	11:50	2.42	12.06	0.73	11.33
Mounting cover	CNC A	11:30	2.35	11.72	0.71	11.01
Eccentric	CNC A	11:45	2.41	11.97	0.72	11.25
Shaft	CNC B	12:29	2.56	11.95	0.77	11.95

**Figure 65: Metal working fluid consumption and related costs**



## 4.6.Overlap of Cost reduction an Environmental Impact

The goal of this study is to identify potential overlaps of cost reduction and environmental impact. Based on the LCA results of section 4.4 and the results of the analysis of the costs for coating and metal working fluid in section 4.5, in the overlap of both can be determined (see Figure 66).

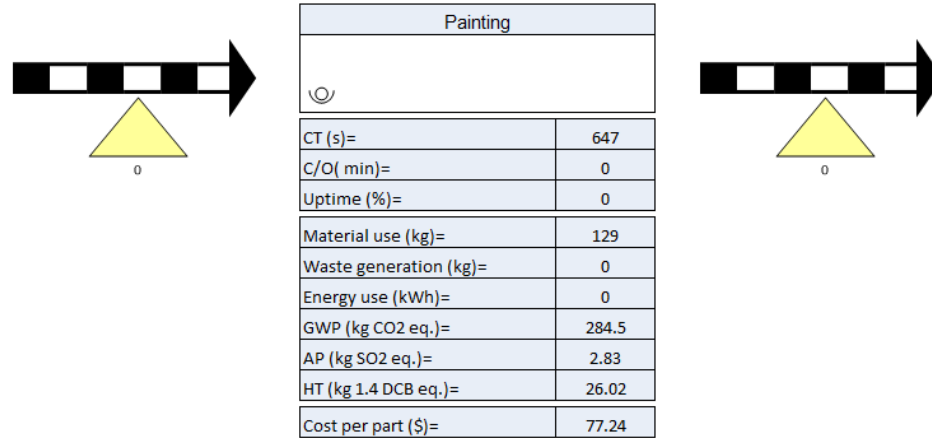


**Figure 66: Comparison of Reduced Impact and Cost Savings for 10000 IEUs**

As shown in Figure 66 the optimization of model 2 and 3 not only reduce the environmental impact during the manufacturing phase, the also lead to cost savings for the manufacturer. If these changes are applied to the current production system, the environmental impact can be reduced by 5% of the overall emissions and save about \$133.75 per produced IEU. For the annual production this means \$1,337,559.

## 4.7. Visualization of the results in a Value Stream Map

The results from the LCA and cost analysis become the input for an adjusted value stream map that includes environmental and cost aspects (see Section 3.5.). As an example, the painting process of the IEU is shown in Figure 67.



**Figure 67: The painting process of the IEU visualized in a VSM**

The complete Value Stream Map of the current state model is shown in Figure 68. It supports the manufacturer tracking the environmental impact and costs within his production system and makes different processes easier to compare.

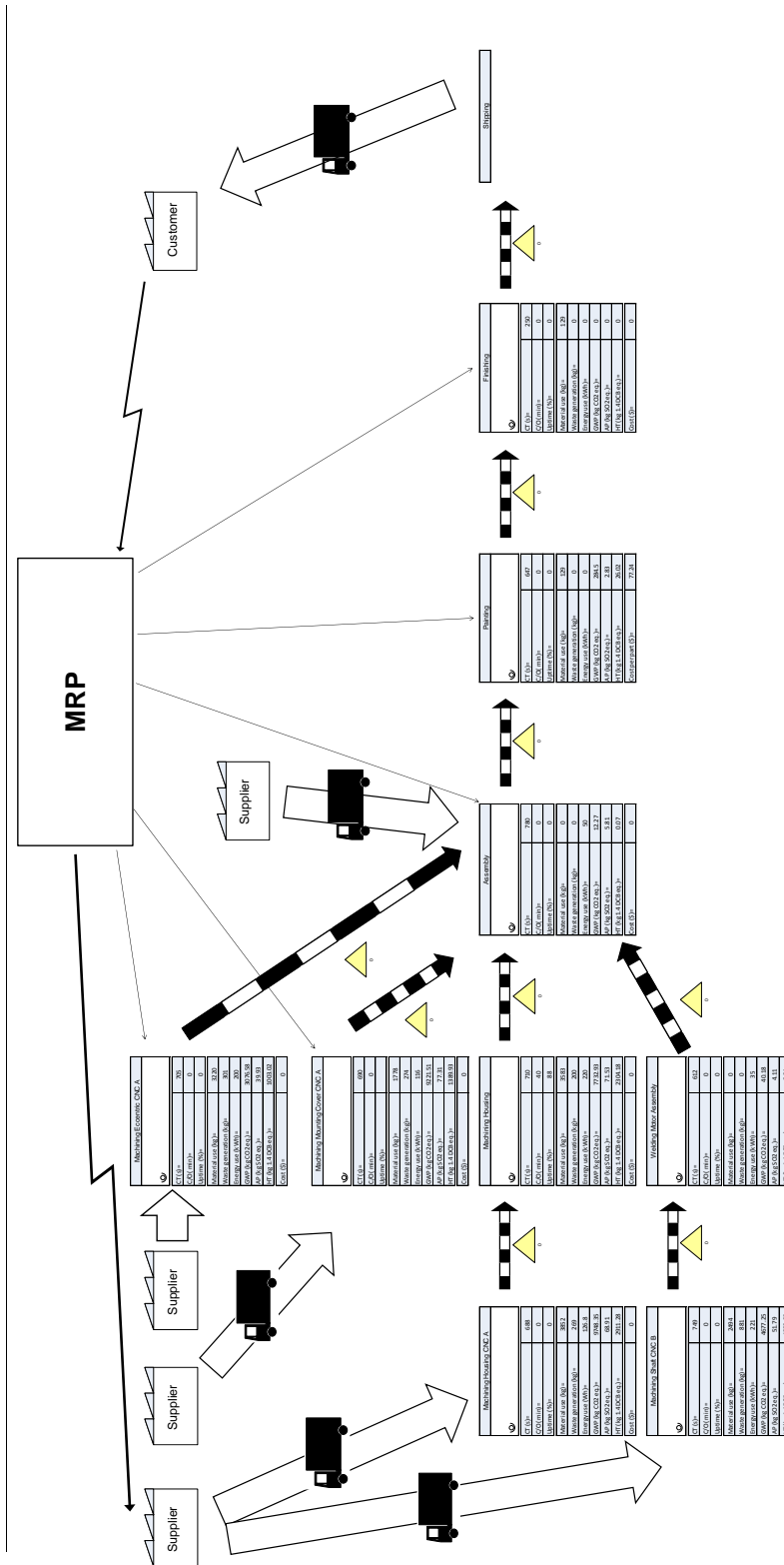


Figure 68: Value Stream Map of the current state model

## CHAPTER 5 – CONCLUSION

In the beginning of the study, the basic concept of sustainability and sustainable manufacturing was presented. Additionally, a comprehensive literature review of the main environmental impact factors during manufacturing was given. Furthermore, Life Cycle Assessment was explained and different versions of the method were introduced. Finally, different manufacturing processes and their environmental impact were presented.

Sustainability assessment including costs are still rare and are not considered sufficiently. Besides the aspect of increasing sustainability in manufacturing, the study also compared improved sustainability with its effects on the costs of manufacturing. The framework that was developed in this research includes different sustainable indicators according to the three dimensions of sustainability. These indicators were evaluated due to criteria that were selected for different issues. Furthermore, the framework includes the use of LCA software. Therefore, different software was evaluated and ranked. To include the cost aspects, CACE-Software was selected to estimate costs for improvements. Finally, all results were represented in a Value Stream Map, where the indicators for environmental impacts and cost were added.

Based on the given framework, a case study was conducted to test the usability of the framework. The analyzed product was an Industrial Equipment Unit from a manufacturing company. After the main components and the manufacturing process of the IEU were explained a LCA of the current state was performed. As part of the LCA

primary data such as: energy consumption, scrap production and waste generation were collected.

The scope of the LCA was to evaluate the environmental impact of manufacturing processes and to identify the biggest contributors of emissions. Therefore the software Umberto NXT LCA was used with the ReCiPe midpoint method. Two types of models were developed based on the collected data. The first model presents the current state of the system while the other types of models simulated an optimized future state version. In one of the future state models, the mineral based metalworking fluid is replaced by a coconut-oil based fluid. In another, the painting process is replaced by either a powder coating process or by an uncoated option. The LCA showed that greatest impacts are due to the production of blank aluminum casting, which is an external process in the raw material phase and not under the influence of the manufacturer. However, the optimizations in model 2 lead to an overall reduction of impacts by 5%. By including cost aspects in the analysis, it was shown that the optimizations in model 2 and 3 would also have economic benefits for the manufacturer. By applying the changes of model 2 \$56.52 can be saved per IEU produced. By applying the changes of model 3 about \$77.24 can be saved per IEU produced.

## **5.1.Discussion**

In this section the reliability of the models that were developed reviewed. In addition, the defined goals are discussed. The first point of discussion is the model software itself. Umberto NXT LCA is a European software which might not consider

the different environmental mechanisms within the United States. This might influence the characterization of emissions or the determination of the indicators. This software setup cannot be adjusted. In contrast to that, processes can be chosen due to their origin. For example, the market for electricity in the East North America is chosen to respect the national characteristics for energy production and distribution. However, this adjustment is not possible for all processes. The market location for aluminum and iron castings is chosen as a global market because there is no other option. Since there is no other LCA software or database specially developed for the United States, this point of critique cannot be changed and is accepted.

The next point is the input data. The results of section 4.2 are used for the models. The reliability of these measures can be stated as satisfying. The problem is that collected data like the cycle times and energy consumptions of the machining processes are mixed with calculated values like the amount of metal working fluid. The CNC-machines used for the manufacturing of the IEU also manufacture other products; hence it was not possible to measure the actual consumption. Therefore, the calculation is considered as acceptable, but not ideal. These shortcomings result in several research options in the future.

## **5.2.Further research**

The most important tasks are the reduction of solid scrap such as aluminum, iron and steel. This could be achieved by using blank components which are closer to the final dimensions of the components and require less machining. This would also decrease energy and metalworking fluid consumption. Alternatively, further research

should investigate if it is realistic to change the material of any components to plastic or iron casting. For the iron casting it has to be investigated whether the extra weight of the product leads to higher shipping costs and whether these costs exceed the potential savings in comparison to cast aluminum. Furthermore, higher weight also leads to higher fuel consumption during transportation which causes a higher environmental impact during the shipping phase.

Another task for further research would be to include the customer opinion on the product, since it is important for the company to convince the customers that all changes did not adversely influence the quality of the product. Further research could also investigate if customers might be willing to pay more for an environmentally friendly product. Furthermore, changing to unpainted versions of the IEU also includes losing a distinctive design feature and recognition value of the brand from a signature paint color. Investigating the impact of this design change can be another task for further research.

### **5.3. Contribution**

This study contributes a successful example of how Life Cycle Assessment of a production process in a small company with limited resources can be conducted. The assessment identified the processes and materials that are responsible for a high amount of the environmental impact. It was also found that most of the environmental impact of the IEU is contributed during the raw material phase. This emphasizes the importance of Life Cycle Assessment to get to a better understanding of where in the product life cycle the environmental impact occurs. It also demonstrates the idea that

most of the costs and environmental impact from a product are determined early in the design process, in this case through material selection decisions. Thus, companies that want to lower costs and environmental impact should pay close attention to these decisions.

By developing future state models it was shown that there is potential for further enhancements of the current production process that can lead to less environmental impact. Furthermore, it was shown that there is an overlap of sustainability and cost reduction. The findings can encourage companies to conduct LCA and produce their products more sustainable, which would not only help to keep our planet clean it also would also save the companies' money.



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