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Development of a Practical Method for Sustainable Routing in Manufacturing Enterprises

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DEVELOPMENT OF A PRACTICAL METHOD FOR SUSTAINABLE ROUTING IN MANUFACTURING ENTERPRISES

BY

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ABSTRACT

In the recent years, global warming, a growing world population, and the development of global markets have raised the interest in a more sustainable development. Thus, sustainability has not only become an important issue in society, but also in manufacturing companies and research. The objective is to attune economic, ecological, and social aspects of the industrial manufacturing of products with one another. In this regard, the sustainability of a manufacturing system must also be taken into account when routing decisions are made to manufacture a product.

Therefore, this study presents the development of a method for routing decisions to improve a manufacturing system in terms of sustainability. The requirements for the approach are derived from a broad literature review regarding sustainable manufacturing. A case study is conducted to create an approach that is suitable for a practical application in manufacturing enterprises. Trade-offs between the dimensions of sustainability are found and the advantages of sustainable routing are emphasized. The method is generally designed to be used as guidance for sustainable routing decisions across manufacturing industries.

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Christoph Gerdes

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1. Introduction

This study concerns the role of routing decisions as a means of improving the sustainability of manufacturing systems. In this chapter, the background and motivation for this field of research are highlighted. The problem to be investigated in this study is stated and its significance is explained. Furthermore, the objective of the study and the procedure to approach the formulated problem are expounded.

1.1. Background and Motivation

In the last decades, a significant increase in the global average temperature has been observed. Global warming results from an increased concentration of greenhouse gases in the atmosphere due to anthropogenic emissions. Tremendous consequences of this phenomenon possibly include a rising sea level and melting glaciers (Florides and Christodoulides, 2009). Therefore, governments around the world have already acted in order to mitigate this problem. For instance, goals were set to limit the increase of the global average temperature by reducing the emissions of greenhouse gases such as carbon dioxide (CO_2) (European Commission, 2015).

To achieve this objective, the energy consumption of industrial companies is of particular importance. Figure 1 shows the energy consumption in the United States of America caused by sector in the year 2016. According to this, about 32% of the total energy was consumed for industrial purposes. In fact, industry was responsible for about 27% of the total CO_2 emissions from energy consumption in the same time period (U.S. Energy Information Administration, 2017). Thus, there is a high need for industrial companies to design their processes more efficiently in order to reduce their energy consumption.

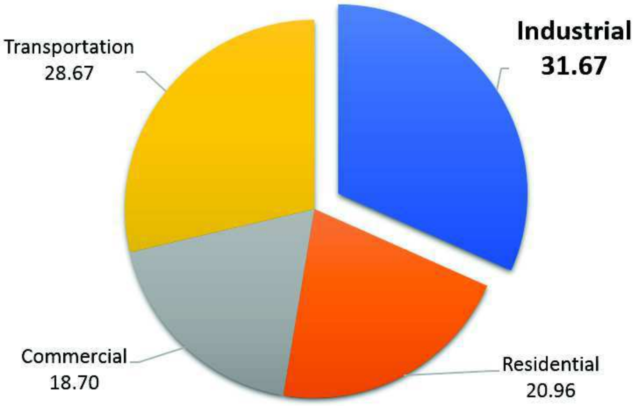

Figure 1. Energy consumption in the United States by sector in 2016 (U.S. Energy Information Administration, 2017)

In the recent years, special attention has been given to manufacturing companies regarding this matter in both practice and research (Duflou et al., 2012). Besides regulations for emissions, other factors have led to a heightened interest of manufacturing enterprises in this field. From an economical perspective, rising energy prices and a trend in customer's behavior towards more environmentally-friendly products make the reduction of energy consumption important (Bunse et al., 2011). Furthermore, manufacturing companies are confronted with the challenge of ensuring the current standard of living for future generations while the world population and its resource demand are growing (Herrmann, 2010).

Addressing all these aspects, the objective of sustainability is to bring economic, ecological, and social goals to an agreement (Thiede, 2012). This presents various challenges and has made sustainable manufacturing one of the most interesting and growing fields in manufacturing research.

1.2. Statement of the Problem

Given the complexity of manufacturing systems, methods developed for sustainable manufacturing must be designed specifically for certain levels of an organization. Thus, various approaches in sustainable manufacturing research have been presented over the last years to improve different aspects of a manufacturing system in terms of sustainability (Duflou et al., 2012).

In this regard, an approach is required that enables companies to account for the sustainability of their production system into account when making routing decisions. Routing decisions are to be made if a part or product can be manufactured via different processes or sequences of processes (Browne et al., 1984). At this point, existing methods only consider economical performance metrics when comparing different process routings with one another. To achieve a more sustainable way of manufacturing, the impact of different routings on the environment and society must also be examined.

Developing a new method for sustainable manufacturing implies some difficulties. For instance, adequate performance indicators for sustainability must be defined. Although various techniques exist to evaluate sustainability, the question is how to apply these for the respective purpose. Additionally, guidelines need to be developed to align economic, environmental, and societal goals with one another for decision making (Reich-Weiser et al., 2010).

In order to develop a new method for sustainable routing, all these issues must be taken into consideration. Furthermore, a review of methods available for sustainable manufacturing shows that existing approaches often lack practicability. Thus, the new method must also be designed to be applicable under the circumstances existing in a real company.

1.3. Objective and Procedure

The scope of this study is to provide a method for manufacturing companies to improve their production systems by making sustainable routing decisions. To ensure the viability of the method, a case study is conducted in which the elaboration of such an approach and its advantages for a manufacturing system are shown. Based on this example, a general framework is to be developed that is scalable for multiple applications in manufacturing industries. The procedure of this study is illustrated in Figure 2.

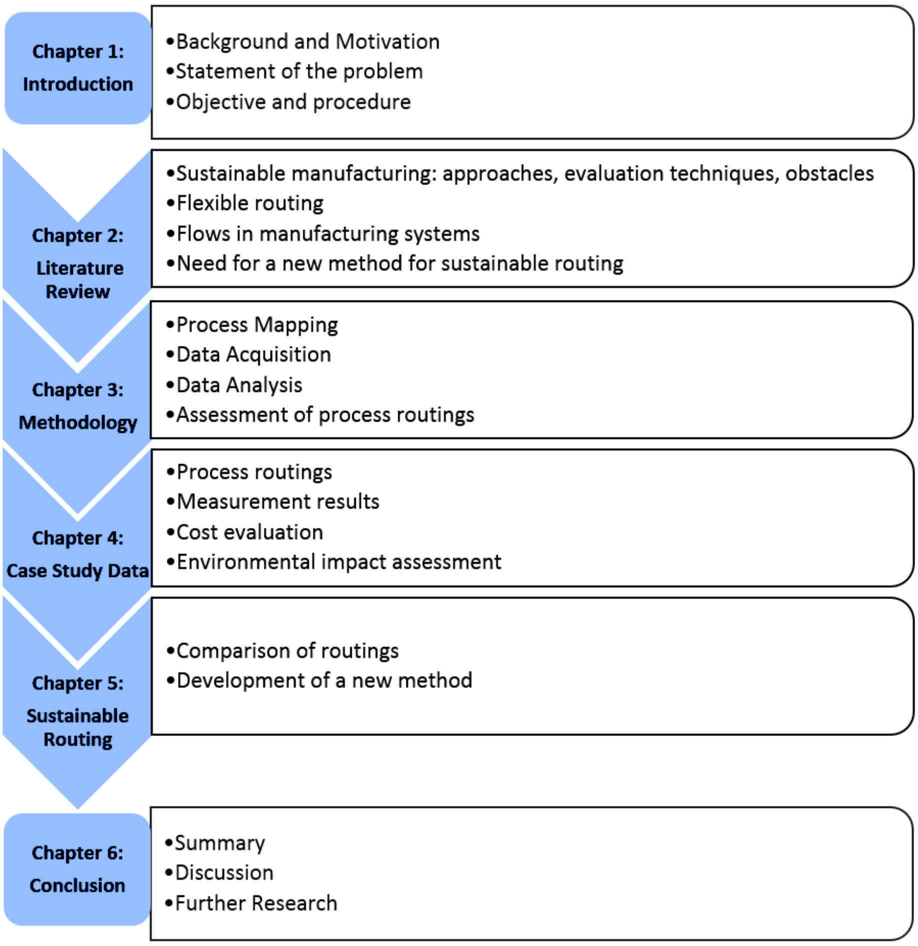

Figure 2. Overall procedure of the study

In the next chapter, a broad literature review regarding the research field of this study is presented. In order to give an overview of the topic of sustainable manufacturing, existing approaches, evaluation techniques, important flows within a manufacturing system, and obstacles are described. Based on the current state of the literature, the need for a practical method for sustainable routing is pointed out. In Chapter 3, the methodology to create this approach and the procedure to conduct the case study are explained. Within the case study environment, various potential routings to manufacture a product are investigated. The data gathering, analysis and assessment are delineated. The outcomes of the acquisition and the analyses of the data are given in Chapter 4 along with graphical representations of the results. In Chapter 5, the different routings in the case study are compared with one another and evaluated in terms of their sustainability. The benefits of making sustainable routing decisions within the company are expressed. Based on this example, a conceptual approach is developed which can be used as guidance for sustainable routing in manufacturing enterprises. The results of this study are summarized and critically reviewed in Chapter 6. Based on the discussion of the achievements of this study, recommendations for further research are given.

2. Literature Review

To point out why a practical method for sustainable routing in manufacturing is needed, the related literature in this field of research is reviewed in this chapter. This includes a definition of sustainable manufacturing and a description of the state of the art in flexible routing. Different approaches for sustainable manufacturing are investigated, and selected techniques to evaluate the energy and material flows in production processes are presented. Furthermore, research regarding obstacles that manufacturing companies are confronted with when trying to become more sustainable are studied. Finally, the need for a new method for sustainable routing is explained based on the reviewed literature. The structure of this chapter's procedure is illustrated in Figure 3.

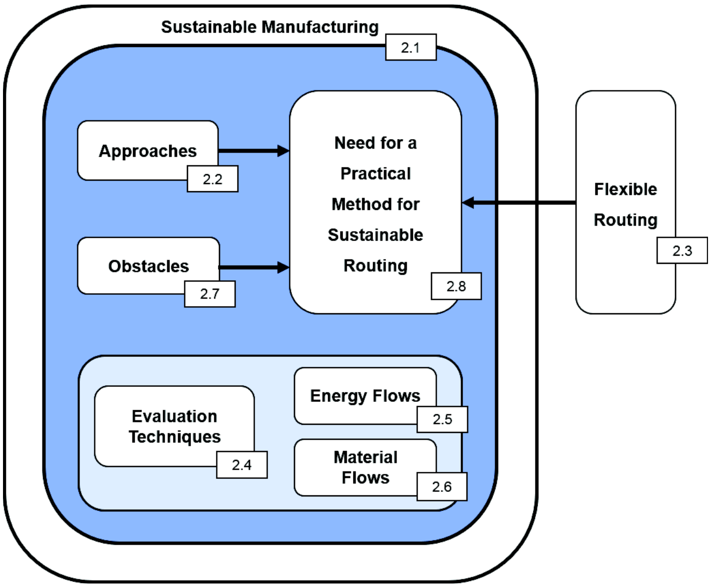

Figure 3. Structure of the literature review

2.1. Sustainable Development

First, it must be clarified what sustainability actually means and why it is an important issue in the industrial manufacturing of goods. Therefore, the term sustainable development and its dimensions are defined. Furthermore, a closer look at the evolution and the relevance of sustainable manufacturing is taken.

2.1.1. Definition and Dimensions

The term sustainable development was coined by the World Commission on Environment and Development in 1987 who define the term as follows: *"Humanity has the ability to make development sustainable to ensure that it meets the needs of the present without compromising the ability of future generations to meet their own needs"* (World Commission on Environment and Development, 1987).

Sustainability includes three dimensions, referred to as the triple bottom line. These dimensions are economy, environment, and society. Addressing all three dimensions ensures the achievement of economic growth while taking environmental and social impacts of that growth into account (Remmen et al., 2007).

Figure 4. The triple bottom line of sustainable development (Herrmann, 2010)

The triple bottom line and the interactions between the three dimensions are shown in Figure 4. A closer look at each dimension and how it should be devised in order to contribute to a sustainable development is displayed in Table 1.

Table 1. Dimensions of sustainable development (Herrmann, 2010)

Dimensions	**Example**
Economy	- meet needs on an individual and societal basis - create competition that stabilizes markets and encourages innovations to face long-term challenges - prices should be the leading influence factor on markets
Environment	- do not exploit renewable sources more than they can regenerate - do not overload the environment (e.g. with emissions into the atmosphere) - use fossil energy sources only as much as they can be replaced by other resources
Society	- keep social peace by providing dignity and individual freedom for all human beings - ensure current societal performance level for future generations at the very last

To achieve those objectives for the different dimensions, the following three main strategies for sustainable development exist (Herrmann, 2010):

- Efficiency strategy

  Efficiency describes the ratio between the inputs and the outputs of a process. For instance, an efficiency strategy is to minimize the resources required to produce one unit of output.

- Consistency strategy

  A consistency strategy aims to achieve a compliance of economy and ecology. This means connecting anthropogenic and natural flows.

- Sufficiency strategy

  Sufficiency means that people take individual responsibility for their resource consumption. This implies a change in people's behavior and in their consumption patterns.

As these strategies affect all different kinds of components of people's lives, sustainable development has also become a relevant issue in the manufacturing of goods. Regulatory guidelines and market changes have forced companies to turn to more sustainable ways of manufacturing. Thus, sustainable manufacturing has also become a very important topic in research (Herrmann et al., 2014).

2.1.2. Sustainable Manufacturing

To understand where sustainable manufacturing has evolved from, a brief overview of the history of manufacturing is provided. Manufacturing has undergone various transitions over the years. Figure 5 shows the transformation from craft production to mass customization.

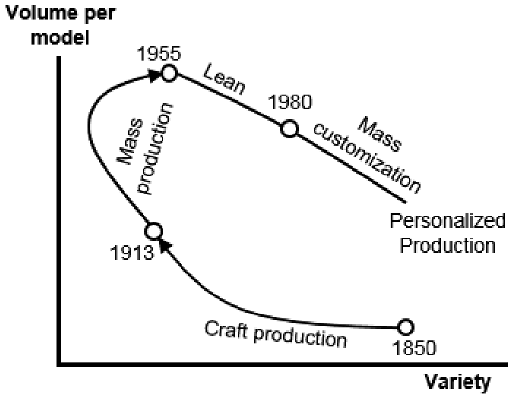

Figure 5. Paradigms of manufacturing (Hu et al., 2011)

In craft production, a product was manufactured in the exact way the customer wants it. This resulted in high production costs. Followed by that, mass production was established allowing for the creation of higher volumes of products at lower costs. However, the downside of mass production was a low variety of products (Hu et al., 2011). This is indicated by a popular quote from Henry Ford: *"Any customer can have a car painted any colour that he wants so long as it is black"* (Ford, 2007).

Trying to make production processes more efficient, the concept of lean manufacturing evolved from the Toyota Production System. It calls for the elimination of waste in the process and increasing efficiency of the production system by continuous improvement (Womack et al., 1990). Responding to the customer demand for a large product variety, the paradigm of mass customization emerged in the late 1980s (Hu et al., 2011).

During the early 2000s, researchers began to consider environmental issues in manufacturing. Allen et al. (2002) investigated how companies can achieve economic growth while protecting the environment. By evaluating efforts and the state of the art by that time in the USA, Europe, and Japan, they identified different motivation factors for sustainable manufacturing. Regulative emission standards, rising resource costs, and the desire to present a green corporate image require more environmentally friendly production of goods (Allen et al., 2002). Other drivers for increasing attention on sustainability in manufacturing include a growing world population and a trend of customer demand towards more environmentally friendly products (Herrmann et al., 2014).

Figure 6 gives an overview of the most important categories of drivers for sustainable manufacturing. The figure categorizes different drivers by using a push/pull view on a company. Examples are given for each category. All drivers share the commonality that they increase the importance of sustainability in manufacturing. Prioroties not only include economic objectives such as cost, time,

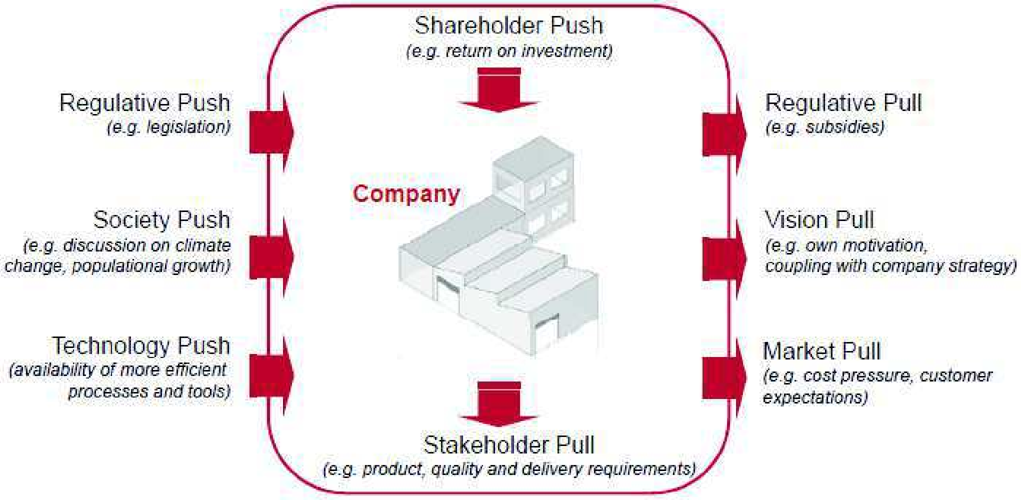

Figure 6. Drivers for sustainable manufacturing (Fichter, 2012)

and quality anymore, but environmental subjects are added to the overall goal of a manufacturing company as well. Considering the triple bottom line and also involving the social responsibility of companies, it becomes the goal of manufacturing companies to align economic, ecological and social objectives with one another. Thus, this calls for a new paradigm of manufacturing: Sustainable Manufacturing (Thiede, 2012).

2.2. Flexible Routing in Manufacturing Systems

A manufacturing system can be flexible in many ways. One type of flexibility in manufacturing is routing flexibility (Browne et al., 1984). A routing is a sequence of workstations that a part travels (Hopp and Spearman, 2001). In this context, flexibility exists if a part or product can be produced via multiple routings. This means that certain steps in the manufacturing process can be done on multiple machines (Browne et al., 1984). A schematic illustration of a multiple routing case can be seen in Figure 7. In this example, a part can be processed through three routings: A+B, A+C+D, and E+F+D. As machine A occurs in two of the routings, it must be noted that one machine can be a part of multiple routings.

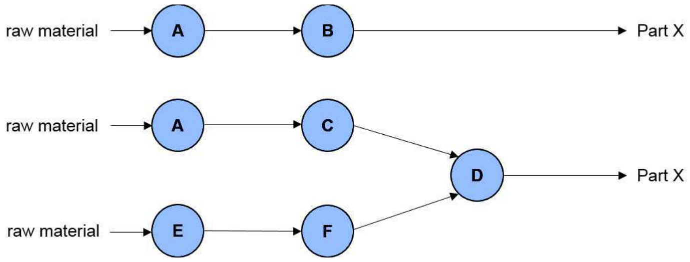

Figure 7. Example for multiple possible routings in processing a part

In some systems, routing flexibility is just an option to face unpredictable events. For instance, a product can be rerouted if a machine breaks down to keep the required production rate (Browne et al., 1984). Furthermore, many works in literature investigate the possibility of taking advantage of multiple routings available for parts to avoid deadlocks in manufacturing systems (Lawley, 1999) (Ezpeleta et al., 2002).

In other systems, a part or product is processed on different routings as a rule (Browne et al., 1984). Thus, different works in literature have generated routing rules to benefit from the existing flexibility in the system. In general, traditional performance indicators like cost, makespan, idle times of machines, tardiness, and lateness are the deciding factors in comparing different routings and rules with one another (Bobrowski and Mabert, 1988) (Yao and Pei, 1990). However, this study focuses on comparing different routings with each other in terms of their sustainability performance.

2.3. Approaches for Sustainable Manufacturing

From an organizational perspective, the production of goods involves activities on different levels of an enterprise. It can be distinguished between four organizational levels. These levels include the product itself, an individual machine, a whole facility or line, and the entire supply chain (Reich-Weiser et al., 2010). The facility or line level is often referred to as system level (Dai et al., 2013). This term is also used in this study. Figure 8 illustrates the four levels of an organization. A differentiation among these levels for existing approaches for sustainable manufacturing is presented in the following sections.

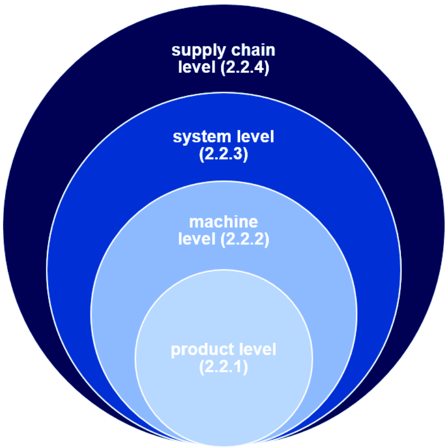

Figure 8. Organizational levels of a manufacturing enterprise

2.3.1. Product Level

Methods on the product level are be explained briefly in this section as the environmental impact of products is a critical factor for achieving sustainability in manufacturing (Ramani et al., 2010).

When it comes to sustainable design of products, all phases of the product life cycle need to be considered. For instance, this includes designing a product suitable for environmentally benign manufacturing processes as well as for recycling purposes in the end-of-life phase. Figure 9 illustrates the different life phases of a product that need to be considered in choosing a sustainable design (Ramani et al., 2010).

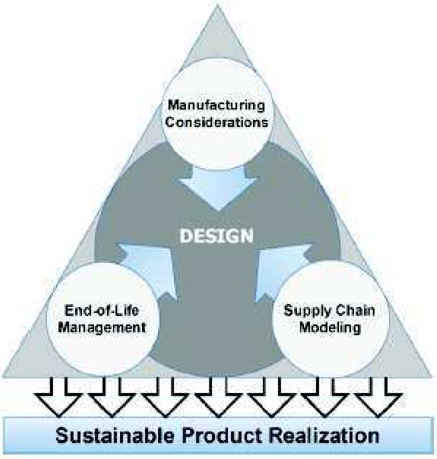

Figure 9. A sustainable product design process (Ramani et al., 2010)

With regards to the manufacturing considerations, Rahimifard et al. (2010) present a model framework for analyzing the energy needed to produce one unit of a product. The used energy is divided into direct and indirect energy. The direct energy is consumed for the actual manufacturing process while the indirect energy is required to maintain adequate production conditions. The amount of all energy types to manufacture one unit of a product is defined as embodied product energy. Changes in the product design can improve the energy efficiency of the production. For instance, more efficient materials could be selected or the design could be adapted to more environmentally friendly manufacturing processes (Rahimifard et al., 2010).

To redesign a product with regards to sustainability, the framework of design for manufacturing and assembly (DFMA) can be extended. While the approach originally aims to reduce the costs of manufacturing, it has the capability to also consider environmental decision factors for sustainable manufacturing (Ramani et al., 2010). For instance, Suresh et al. (2016) present an approach for the integration of both the design for environment and the design for manufacturing and assembly. A change in the design of the component through the method presented in this work reduces the environmental impact and the costs of the component (Suresh et al., 2016).

However this study does not consider different options of designing a product, but investigates possible process routings to manufacture a part. For this reason, the focus is on methods regarding the actual production process in the following sections.

2.3.2. Machine Level

The work by Sheng and Srinivasan (1995) is one of the first that adresses sustainable machining processes. The environmental impact of manufacturing processes can be reduced by designing the process efficiently. This includes finding alternative ways to produce a part which are more sustainable. At the machine level, these different ways are determined by setting the process parameters. A decision-making model is developed to find the optimal settings for the process parameters (Sheng and Srinivasan, 1995). The model is shown in Figure 10.

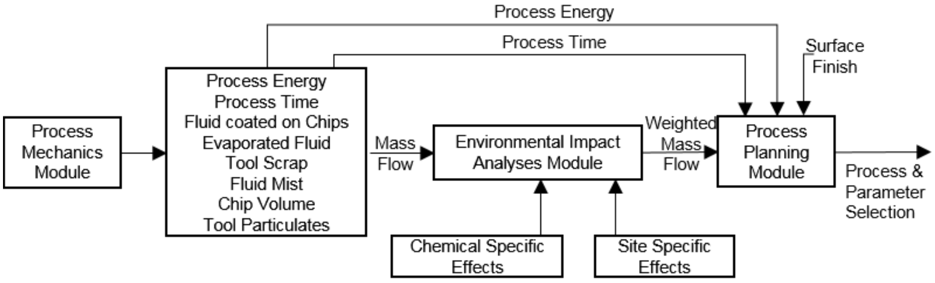

Figure 10. Setting optimal process parameters (Sheng and Srinivasan, 1995)

According to this model, four performance indicators of a manufacturing process on a machine are used to select the best process design:

- Process energy
- Process time
- Environmentally weighted mass flow
- Quality

To find the optimal process settings, a prioritization matrix is used to make the different objectives comparable with one another (Sheng and Srinivasan, 1995). In a further work, a case study is conducted using this approach to investigate the effects of changes in process parameters on the environmental impact of material removal mechanics, tool life, scrap production, and cutting-fluid flow. Estimating these effects contributes to the development of a more sustainable way of machining (Munoz and Sheng, 1995). Although these are older works, they show how a framework can be designed to implement sustainability in manufacturing.

In more recent works, researchers focus on the influence of different kinds of process parameters towards energy consumption of machines and try to find optimal parameter settings for certain machining processes. A few examples are as follows:

- An investigation of which material removal rate should be selected for a certain process in order to reduce the energy consumption (Kara and Li, 2011)
- Case studies on the influence of cutting conditions, possibilities of power savings during deep hole drilling, and the role of spindle and servo motors to reduce the power consumption of machines (Mori et al., 2011)

- An analysis of the effect of varying thicknesses and material strengths on the energy consumption and the material waste resulting from sheet metal forming processes (Ingarao et al., 2012)

All the mentioned works prove that it is possible to reduce the energy consumption of machining processes by adapting the process parameters. However, all these works only focus on the material removal process. Dahmus and Gutowski (2004) point out that the energy consumption of production machines is caused by more than just the actual material removal process. Auxiliary components of a machine, such as oil pumps and coolants, also consume energy. In comparison to the material removal process, the energy consumed by the supporting equipment is constant and does not depend on the process parameters. Additonally, it is proven that the energy share for material removal is rather small regarding the total energy consumption during the process (Dahmus and Gutowski, 2004).

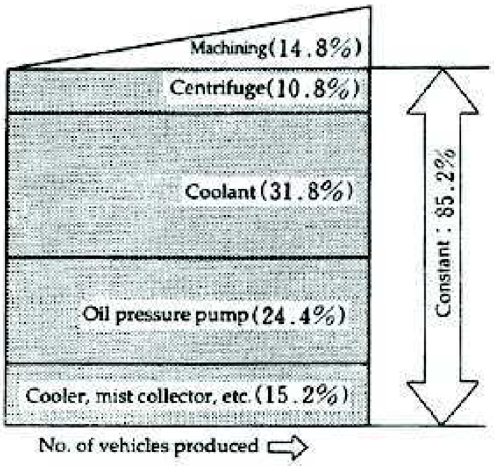

Figure 11. Example for breakdown of energy consumption of a production machine (Gutowski et al., 2006)

Figure 11 shows an example of a breakdown of the electrical energy consumption of a machine at an automotive manufacturer. This figure demonstrates that out of the total energy consumption only 15% is actually used for the machining process. There is significant energy consumption in starting a machine and then keeping it in a state where it is ready for processing a part. Thus, energy requirements of machines are often dominated by supporting functions of the machine and not by the actual process itself (Gutowski et al., 2006).

This means that measures regarding the optimization of the machining process have a relatively low contribution to increasing energy efficiency in manufacturing. The major share of the energy needed by a machine is required when the machine is in an idle phase. Reducing the energy consumption during idle times cannot be done by changing process parameters. To reduce idle times, actions regarding the entire production system are needed. This is where approaches on the machine level reach their limits and a system perspective is required.

2.3.3. System level

Optimizing schedules on a system level can lead to significant energy savings with only small investments required. For instace, Fang et al. (2011) create a multi-objective optimization model for flow shop scheduling which aims to minimize the makespan, the peak power consumption and the carbon footprint. Although pareto-efficient schedules can be found, they conclude that the computation time is too large for an application on an industrial scale (Fang et al., 2011).

In order to reduce energy consumption by adapting machine scheduling, Mouzon et al. (2007) try to design a machine controller to optimize the energy usage of a machine. The decision at hand in order to save energy is whether to turn an idle machine off or to keep it running during idle times. A multi-objective model is presented to minimize the total completion time of jobs and the total energy consumption (Mouzon et al., 2007). In an additional work, an algorithm is presented that can find pareto-optimal solutions. However, the trade-off between the objectives makes the problem difficult to solve. The decision maker must first set preferences for the objectives in order to reach a solution (Mouzon and Yildirim, 2008).

The problem of scheduling in a flexible flow shop is also investigated by Dai et al. (2013) who specify the problem in a more detailed manner. A flexible flow shop layout is illustrated in Figure 12. A job must go through a certain number of production stages to be completed. At least one machine at each stage and at least one stage with more than one machine are assumed. Each job has a corresponding processing time and power consumption for each machine. In scheduling, each job is assigned to machines at each stage to achieve certain objectives (Dai et al., 2013).

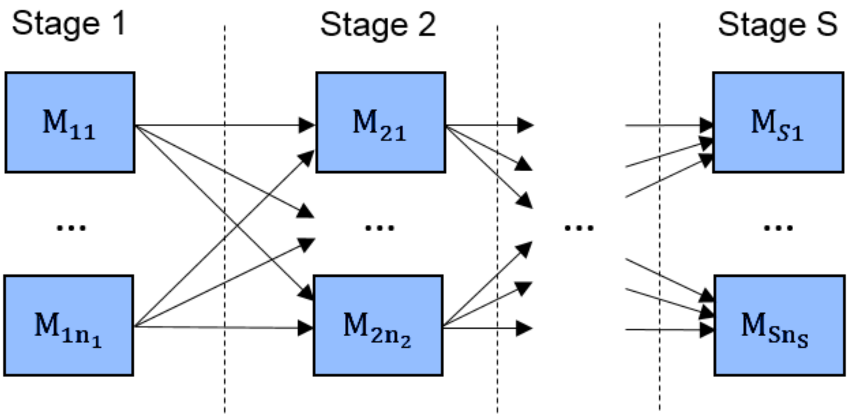

Figure 12. Flexible flow shop layout (Bruzzone et al., 2012)

For instance, the minimization of the tardiness and the makespan of jobs are used as objectives in the work of Bruzzone et al. (2012). Their model shows that a certain peak power demand can be satisfied while the makespan and the tardiness are minimized (Bruzzone et al., 2012). In constrast, the multi-objective model by Dai et al. (2013) aims to minimize the maximum completion time of jobs and the total energy consumption. Energy-savings are achieved by turning off idle machines as Mouzon et al. (2007) suggested in their work. This approach is illustrated schematically in Figure 13. Energy can be saved, if the energy required to start the machine again after turning it off is less then the energy consumed during idle times. Due to the conflicting relationship between the objectives, only pareto-optimal solutions can be found with the decision-maker setting preferences. (Dai et al., 2013).

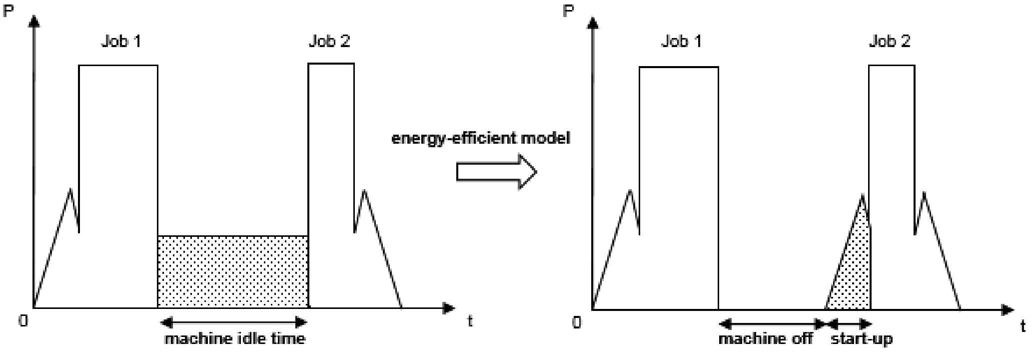

Figure 13. Schematic illustration of the energy-saving approach (Dai et al., 2013)

Other works in this field of research deal with minimizing the total carbon emissions by using scheduling models to reduce the environmental impact (Ding et al., 2016) or investigate the energy-efficient scheduling problem in a job shop (Liu et al., 2014). To account for uncertain events that occur in real-world scheduling problems, Tang et al. (2016) present a dynamic scheduling model. The arrivals of new jobs and machine breakdowns are considered in their model giving a strong example of the inclusion of dynamic factors in a scheduling problem (Tang et al., 2016).

Lastly, it must be mentioned that there are some approaches on the system level in energy-efficient manufacturing that focus not on the reduction of energy itself, but rather on the reduction of the cost resulting from energy consumption. An example in this case is the work of Luo et al. (2013) which discusses the reduction of electric power costs. Time-of-use prices for the electric power consumption are considered which differ for different seasons and weekdays (Luo et al., 2013). Figure 14 shows an example for different price periods.

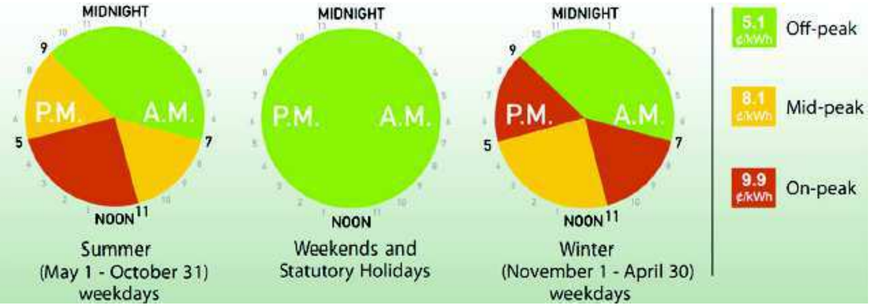

Figure 14. Example for time of use energy prices (Luo et al., 2013)

The idea is that scheduling can be used to shift certain operations from peak periods to non-peak periods in an effort to save energy costs. The reduction potential increases with the length of each pricing period. However, shifting operations conflicts with the makespan leading to a trade-off (Luo et al., 2013). It should be noted that although this approach focuses solely on the economical side of the problem and does not contribute to real energy savings, it might be practical for companies in real-world applications.

2.3.4. Supply Chain Level

"A supply chain is defined as a set of three of more entities (organizations or individuals) directly involved in the upstream and downstream flows of products, services, finances, and/or information from a source to a customer" (Mentzer et al., 2001).

Sustainable supply chain management is the management of these upstream and downstream interactions with heightended regard to reduce the negative environmental and societal impacts. Besides considering the internal processes at the different locations of the supply chain, this also includes examining the transportation processes between facilities. The energy demand for transportation processes mainly depends on the distance and the type of transport. Regarding the distance between facilities, is must be noted that supply chains are often organized globally. This means that goods need to be shipped between different countries, or even different continents. The locations of the facilities also dictate the chosen type of transport. It is distinguished between transports by road, air, rail, and water. Depending on the transport mode, different fuel types can be selected. The fuel type highly influences the amount of atmospheric emissions which causes consequences for the environment (Duflou et al., 2012).

Although transportation processes are an important issue, additional factors need to be considered in order to achieve a sustainable supply chain. Hassini et al. (2012) provide a broad literature review on sustainable supply chains. Based on their findings, they present a framework for sustainable supply chain management. This framework consists of six major supply chain functions that need to be addressed for sustainability (Hassini et al., 2012). These functions, along with an exemplary method for each, are listed in Table 2.

Table 2. Major supply chain functions (Hassini et al., 2012)

Supply chain function	**Exemplary method**
Sourcing	Use of renewable resources
Transformation	Provision of fair labor conditions
Delivery	Tradeoff between times and emissions
Value Proposition	Justify potential higher costs for customers
Customers	Education of customers about sustainability
Reuse, recycle, return	Recycling to new raw materials

There are still many possibilities for further research in the field of sustainable supply chain management. For instance, supply chains of different industries should be investigated. Specific performance indicators, in regards to sustainable supply chains, are needed for certain industries (Hassini et al., 2012).

2.4. Evaluation of Sustainability

To apply methods for sustainable manufacturing efficiently and to assess their benefits, it is necessary to evaluate the performance of a manufacturing system in terms of sustainability. Therefore, two common methods existing in the literature for evaluating sustainability, sustainable value stream mapping and life cycle assessment, are presented in this section.

2.4.1. Sustainable Value Stream Mapping

As described in Section 2.1.2, sustainable manufacturing emerged from other paradigms of manufacturing. Thus, tools that are used in other paradigms might also be applicable or scalable for sustainable manufacturing. Many works in literature explore the relationship between lean and sustainable manufacturing. In this case, sustainable manufacturing is often referred to as ”green manufacturing”. Dües et al. (2013) investigated the similarities and differences between lean and green paradigms for whole supply chains. They concluded that synergies between both principles exist and that lean methods can help to improve the sustainability of supply chains. Lean and green philosophies are most similar in terms of the tools that they use to identify and eliminate waste in the process (Dües et al., 2013).

One of these tools in lean manufacturing is value stream mapping (VSM). VSM is used to visualize the manufacture of a product. It includes all processes, from the raw material provided by a supplier, to the finished product for the customer. Furthermore, it supports discovering the actual causes for waste in the system, so that opportunities for improvement can be identified (Rother and Shook, 1999). However, the traditional value stream map just displays the economic performance of processes by measuring performance indicators such as the cycle time and the changeover time. It does not consider the environmental impact of activities. To make use of VSM as a tool for sustainable manufacturing, the method must be extended to also visualize the state of a manufacturing system in regards to its sustainability (Faulkner and Badurdeen, 2014).

Different approaches exist in literature for creating this extension. Focusing on energy effieciency in manufacturing, Erlach and Westkämper (2009) expand the traditional value stream map to an energy value stream map. Therefore, the energy consumption of the manufacturing equipment needs to be identified. The term energy intensity is defined to evaluate the energy usage and make it comparable between different consumers. The energy intensity is the energy consumption per day divided by the number of units per day (Erlach and Westkämper, 2009). Another approach is presented by Kuriger and Chen (2010) who refer to the extension of the original VSM as energy and environment value stream map. A set of icons is provided for visualizing the different forms of energy and materials used in manufacturing. Material usage is considered by showing the input and output materials of a process. The actual usage can be determined by calculating the difference between the inputs and outputs (Kuriger and Chen, 2010).

Dadashzadeh and Wharton (2012) apply green value stream mapping to increase the sustainability of the information technology department of an organization. An important step named is the implementation of a sustainable way of thinking within an organization to examine the environmental performance of processes. Like with a traditional VSM, the goal is to eliminate wastes in the process. Particularly, the seven green wastes established by Wills (2009) are targeted which are listed in Table 3. These include costs for the consumption of resources that impact the environment, such as the consumption of energy or greenhouse gas emissions caused by transportation of materials (Dadashzadeh and Wharton, 2012).

Table 3. Green wastes (Wills, 2009)

Waste	Definition of waste
Energy	Costs resulting from energy consumption which has a negative impact on the environment
Water	Costs for water usage and waste water treatment
Material	Material usage to manufacture products
Garbage	Costs for the pruchase and disposal of material that negatively affects the environment
Transportation	Costs for unneccessary transportations that cause atmospheric emission by using fossil fuels
Emissions	Costs and fines for emitting pollutants
Biodiversity	Costs for the devastation of natural habitats

In comparison to the works referenced above, Faulkner and Badurdeen (2014) presented a method to show the performance of a manufacturing system with regards to all three dimensions of sustainability, referred to as sustainable value stream mapping (Sus-VSM). The objective is to identify metrics that should be added to the economic performance indicators assessed in a traditional value stream map. Metrics to measure the environmental performance of processes and societal metrics to evaluate the impact of manufacturing processes on the health and safety of employees are distinguished. The metrics added for the environmental and societal dimension to create a sustainable value stream map can be seen in Table 4 (Faulkner and Badurdeen, 2014).

Table 4. Metrics for Sus-VSM (Faulkner and Badurdeen, 2014)

Dimension	Metrics
Environmental	Energy consumption Raw material usage Process water consumption
Social	Physical work Work environment

The process water consumption, raw material usage, and energy consumption are used to measure the environmental impact. For the social dimension, the physical work of the employees is displayed by metering the ergonomics of the workplaces using a scoring system. The work environment is assessed by looking at potential risks for the employees' health and safety. Faulkner and Badurdeen (2014) suggest to using the noise level at the workplace to evaluate the work environment and therefore present an approach on how to measure its effect on the employee. For all the metrics, graphical tools to visualize the measurements in the value stream map are presented. A case study is conducted for a production line in which measurements for the named metrics are taken and a sustainable value stream map is created using the defined nomenclature. Sustainable value stream mapping is assessed as a helpful tool to examine the performance of a manufacturing system in terms of sustainability and thus to identify possibilities for improvements. It must be noted that the usage of specific metrics may depend on the industrial sector in which the method is applied, because certain metrics play a more critical role in some industries than in others. Therefore, metrics that can be used across industries should be identified. For proper visualization of processes, the number of metrics included should also be kept within reasonable bounds (Faulkner and Badurdeen, 2014).

The reviewed literature shows differing approaches regarding the extension of VSM as a tool which can be used for sustainable manufacturing. Regardless of the specific methods presented above, value stream mapping is a useful tool to visualize and evaluate the sustainability of a production system. For future applications, a universal form of sustainable value stream mapping should be created. Some works also call for a key performance indicator that represents all factors of a sustainable value stream map (Kuriger and Chen, 2010).

2.4.2. Life Cycle Assessment

When evaluating sustainability in manufacturing, special attention is given to assess the environmental impact of the production of goods. A common method to analyze the environmental impact of processes and products is life cycle assessment. A life cycle assessment shows the input and output flows related to a product system and evaluates their environmental impact over the total life cycle (Herrmann, 2010). An illustration of the method can be seen in Figure 15.

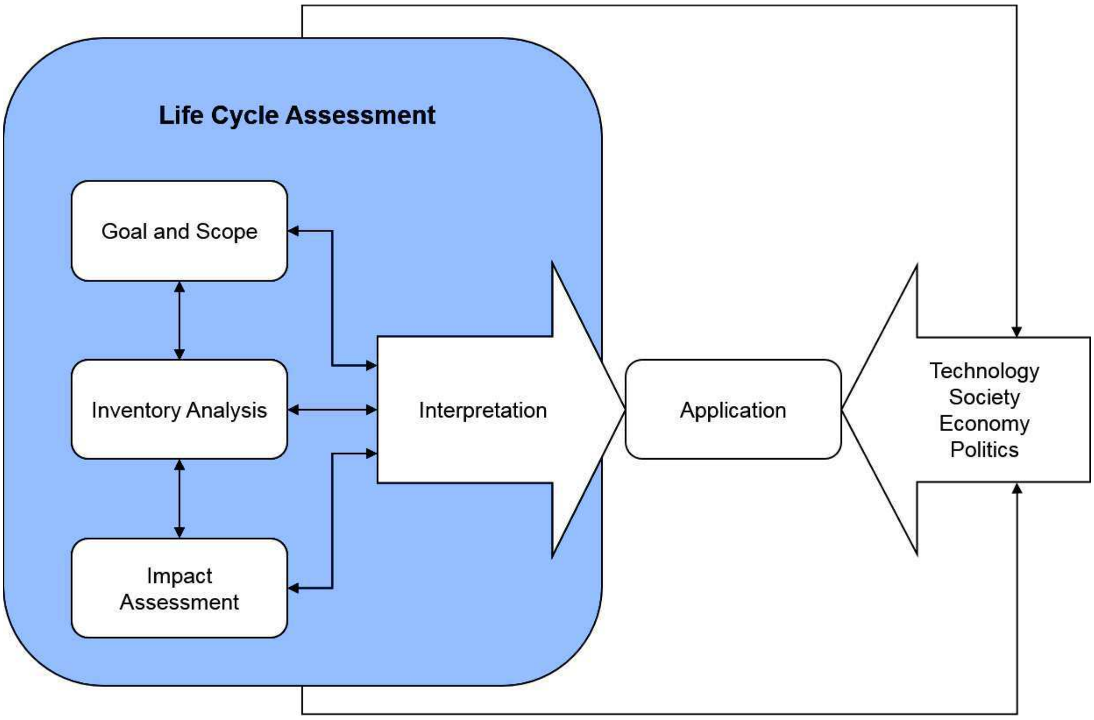

Figure 15. Steps of a life cycle assessment (Herrmann, 2010)

The conduction of the method can be broken down into four iterative steps (Herrmann, 2010):

1. Goal and scope

   The first step includes the determination of the object of study and the study's reasons and objectives. The functional unit as a basis for calculations needs to be clarified.

2. Inventory analysis

   The data for the relevant input and output flows is collected and quantified. To ensure transparency of the data, a detailed documentation of this step is recommended.

3. Impact assessment

   The collected data is analyzed in terms of its environmental impact. Therefore, a classification of the data within different impact categories is necessary. In general, it is distinguished between five environmental impact categories, as listed in Table 5.

Table 5. Environmental impact categories (Herrmann, 2010)

Abbreviation	**Category**
GWP100	Global warming potential
ODP	Ozone depletion potential
POCP	Photochemical ozone creation potential
AP	Acidification potential
NP	Nutrification potential

A short explanation of each of those categories can be seen as follows:

- Global warming potential

  The global warming potential displays the impact of atmospheric gases on the climate. The global warming potential of a gas is measured as the amount of carbon dioxide that contributes the same extent to the greenhouse effect as one kilogram of that gas. It is therefore given in carbon dioxide equivalents ($CO_{2_{eq}}$).

- Ozone depletion potential

  The ozone depletion potential represents the destruction of the ozone layer using trichlorofluoromethane as a reference substance.

- Photochemical ozone creation potential

  The photochemical ozone creation potential displays the creation of smog through nitrous gases. It is measured using ethylene C_2H_4 as a reference substance.

- Acidification potential

  The acidification potential describes the acidification of soils and waters. It is quantified based on the acidification caused by sulfur dioxide SO_2.

- Nutrification potential

  The nutrification potential expresses the eutrophication of soils and waters. It is given using phosphate PO_4- as a reference substance.

4. Interpretation

   The results of the inventory analysis and the impact assessment are analyzed and evaluated with regards to the defined goals of the study. The evaluation should be presented in a way that is useful for decision-making in different fields of application.

However, conducting a complete life cycle assessment requires a multitude of resources and time. Because of this, simplified variations of the method may be applied for certain purposes (Hochschorner and Finnveden, 2003). There are different approaches to streamline the life cycle assessment, including eliminating upstream and downstream stages or focusing on selected environmental impacts alone. It must be noted that the method loses its life cycle perspective with a certain extent of simplification. For instance, this happens when life cycle assessment is just applied for the manufacturing phase of a product excluding all other upstream and downstream phases. In this case, only the processes within a certain facility (gate-to-gate) are examined. Thus, the results and advantages of this streamlined approach are limited to the manufacturer. It is controversial if this still should be referred to as a life cycle assessment. Nevertheless, it is a useful method to evaluate the environmental impact of the processes within a manufacturing system (Todd and Curran, 1999).

2.5. Energy Flows in Manufacturing

Energy is one of the most important factors required in manufacturing. Within a manufacturing system, different types of energy are flowing. Primary energy carriers are converted to effective energy types in order to be used for production processes (Posselt, 2016). In this section, two main energy types used for manufacturing processes, electrical energy and compressed air, are discussed.

2.5.1. Electrical Energy

To measure the amount of electrical energy consumed by production machines, different approaches exist in literature. As indicated in Section 2.3.2, various components of a machine contribute to its total energy consumption (Dahmus and Gutowski, 2004). Therefore, Drake et. al (2006) provide a framework to quantify and analyze the energy consumption of a machine and its subcomponents. This approach includes six steps which are displayed in Figure 16. The framework indicates that the share and the temporal behavoir of each major component must be investigated (Drake et al., 2006). While this was one of the very first approaches in this field, more recent publications suggest the use of automated systems to monitor and analyze the energy consumption of machine tools in manufacturing systems. Automated systems can facilitate the gathering of data from a complex manufacturing system with multiple data sources. For their application, software tools need to be able to meter the energy consumption simultaneously with other process parameters and data sources need to be designed according to a certain standard (Vijayaraghavan and Dornfeld, 2010).

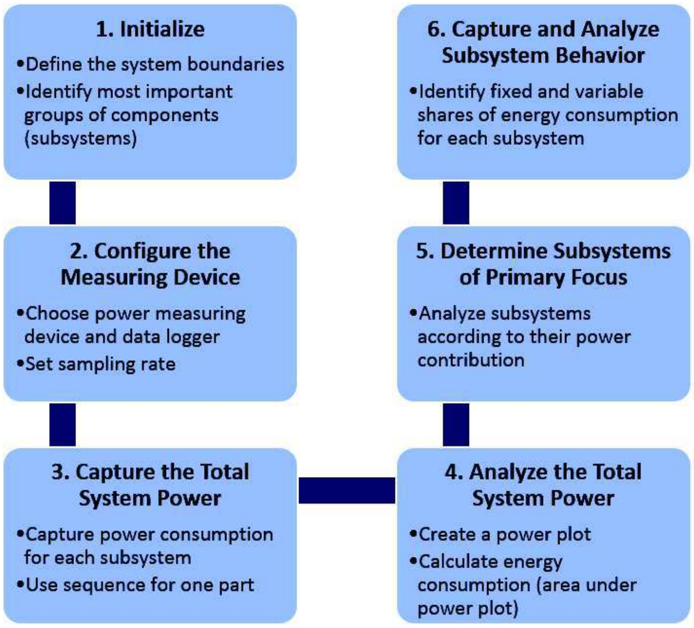

Figure 16. Framework for measuring energy consumption (Drake et al., 2006)

To visualize the amount of power demand over time, energy load profiles can be created. A load profile of a production machine consists of the specific power demands of the respective machine components and displays the energy consumption behavior of the machine for processing a certain product. Energy load profiles indicate that electrical energy consumption is not static, but the amount of power consumed changes over time depending on the production process (Thiede, 2012). An example of an energy load profile of a grinding machine is shown in Figure 17.

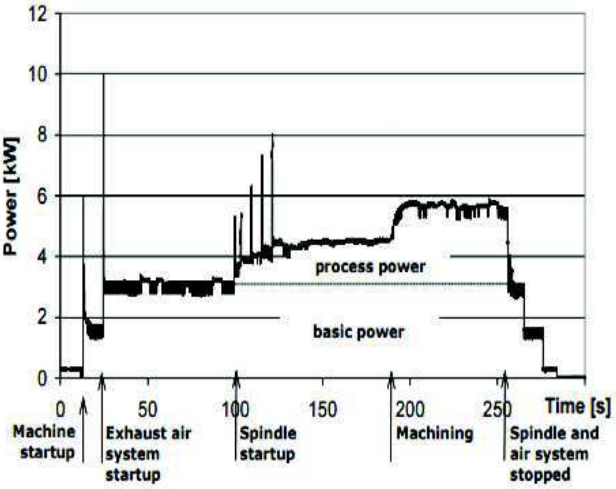

Figure 17. Load profile of a grinding machine (Herrmann et al., 2008)

In this load profile the basic power consumption and the process power consumption are distinguished. While the basic power ensures that the machine is ready for processing, the process power is the power demand for the actual operation. It can be observed that the share of the basic power is relatively high and that peak power demands occur during the start-up of the machine (Herrmann et al., 2008).

By analyzing energy load profiles of machines, different machine states can be observed. In literature, various approaches exist that try to define those machine states and to separate them from one another (Weinert et al., 2011) (Hu et al., 2012) (Behrendt et al., 2012) (Thiede et al., 2012) (Thiede, 2012). Summarizing these approaches, the most common differentiation is between the four states shown in Table 6.

A breakdown of the energy consumption during different machine states is not only important to see the share of the different machine components of the total energy consumption, but also to identify when and why peak power demands occur. The peak power demands play a significant role when it comes to the electricity

Table 6. Energy consumption of different machine states

Machine state	Energy consumption
Off	No energy consumption
Start-up	Switching on main components leads to peak power demands
Idle	Keeping machine ready for processing causes a constant energy consumption
Processing	Energy consumption due to actual operation of the machine

bill. Costs for electricity in manufacturing companies are not just determined by the amount of energy consumed, but rather consist of three main components: costs for the total electrical energy consumption, costs for the power demand, and additional fixed fees. Regarding the power demand, energy suppliers charge extra costs from companies as their instantaneous peak power demand has an impact on the grid (Thiede, 2012).

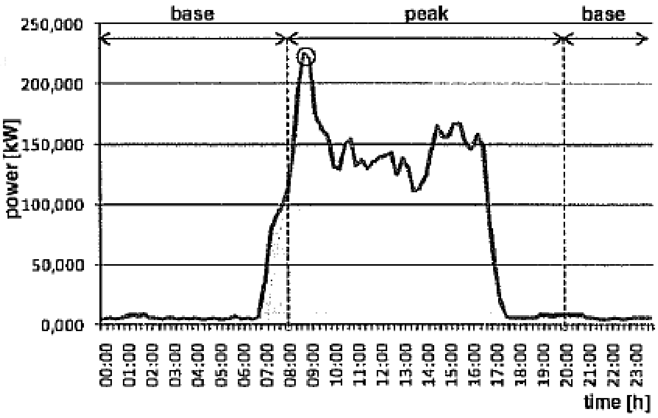

Figure 18. Example for a daily electrical load profile of a company (Thiede, 2012)

For measuring the power demand, the power demand is usually averaged over an interval of 15 minutes. This creates an electrical load profile for one day as shown in Figure 18. To calculate the costs resulting from peak power demands, the highest of these measured values for a certain period is used. This period depends on the individual contract with the supplier, but could be a twelve month historical value. As this part of the electricity costs represents a relatively high amount of the total electricity costs, improvement measures for sustainable manufacturing must also focus on reducing peak power demands (Thiede, 2012).

2.5.2. Compressed Air

Compressed air is used for various purposes in manufacturing companies. For instance, some tools utilize compressed air for the fastening of parts. Other applications are found in the transportation of goods, in painting processes, and in the cleaning of parts and workplaces. The reason for this wide field of usage are the numerous benefits compressed air offers in comparison to other energy carriers. It has positive storage and transportation characteristics and its use does not come along with large safety requirements. Furthermore, it is a pure medium, so there is no necessity for cleaning after its utilization (Thiede, 2012) (Bierbaum and Hütter, 2004).

From a physical perspective, compressed air is generated by converting electrical energy into mechanical energy (Bierbaum and Hütter, 2004). However, the provision of compressed air is affiliated to large energy losses. Less than 10% of the input energy remains usable for the consumer. Besides the heat losses through the conversion process in the compressor, a lot of the losses are caused by leaks in the system. Due to these inefficiencies, compressed air is one of the costliest energy carriers in manufacturing (Gauchel, 2006). The costs of compressed air in comparison to other energy carriers are shown in Figure 19. The costs per one million British Thermal Units (MMBTU) of compressed air are approximately twice as much as for electricity.

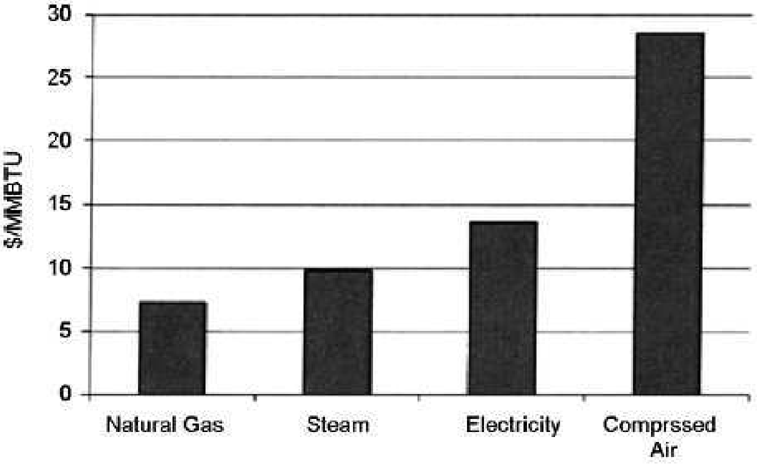

Figure 19. Cost of different energy carriers (Yuan and Zhang, 2006)

In manufacturing, there is often a lack of awareness regarding the costs of compressed air. However, the energy costs for the operation of a compressor exceed the investment costs by far and take a major share of the total life cycle costs, as illustrated in Figure 20. Thus, energy efficiency measures can be cost-beneficial and can lead to savings in the life cycle of a compressor (Saidur et al., 2010).

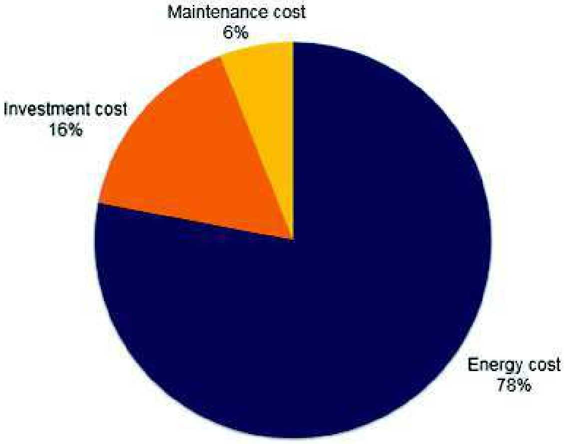

Figure 20. Life cycle cost of a compressor (Saidur et al., 2010)

Several methods for increasing the efficiency of compressed air usage exist and many of them have short amortization times (Saidur et al., 2010). Three examples for improvement measures are presented in Table 7.

Table 7. Examples for improving compressed air usage (Saidur et al., 2010)

Field of application	Explanation
Energy consumption	- variable speed drive for motors to adjust the operation to actual required load level - prevent that systems operate unnecessarily at maximum capacities
Leak prevention	- leaks cause a high share of inefficiencies in compressed air system - continuous maintenance of pipes - ultrasonic acoustic devices for detection
Pressure drop	- pressure is often higher than needed - reduce pressure to lowest functional pressure that is necessary for production

Saidur et al. (2010) review several approaches and data presented in other studies in order to evaluate the potential of different methods to save energy and cost. The result of their study is that various possibilities exist to improve compressed air systems and thus to reduce energy consumption and cost in manufacturing companies. The awareness of the intensive cost and improvement potentials for the use of compressed air must increase in order to achieve maximum benefits (Saidur et al., 2010).

2.6. Material Flows in Manufacturing

A production process is a transformation process in which different input factors are used to produce certain outputs. Input factors are the manufacturing equipment and facilities, energy, working capacity, information, and various forms of materials. Besides the products that the manufacturer seeks to produce, unwanted byproducts, waste, and emissions are also outputs of a production process. Figure 21 illustrates the transformation from inputs to outputs (Schenk et al., 2014).

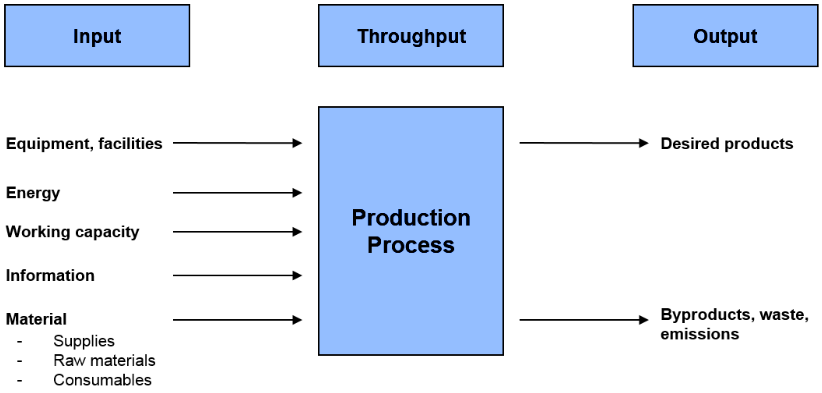

Figure 21. A production process as a transformation process (Schenk et al., 2014)

To include environmental factors into the evaluation of a process, it is necessary to look at the inputs and outputs that seem rather irrelevant by economic standards. Material flows within a manufacturing system are especially important when investigating the environmental impact. For instance, the use of consumables, like lubricants, needs to be analyzed. On the output side, material waste flows need to be considered in addition to the desired products resulting from the process (Herrmann, 2010).

Various works in literature investigated material flows by looking at the inputs and outputs of systems. For instance, these include an input-output analysis on a national economic scale (Bailey et al., 2004) and the development of a matrix model to show inflows, outflows, and the conversion of materials within a system (Xue et al., 2004). To get a better understanding of the material flows in manufacturing and their environmental impact, the use of lubrication oils and material wastes are examined.

2.6.1. Lubrication Oils

In manufacturing processes, lubrication oils are used for machines and tools to reduce friction and attrition (Boyde, 2002). In fact, lubrication and cutting fluids are responsible for a high share of the production costs. Figure 22 shows an example for the cost shares at the German automotive industry where the costs for coolants account for about 17% of the total costs (Sarhan et al., 2012).

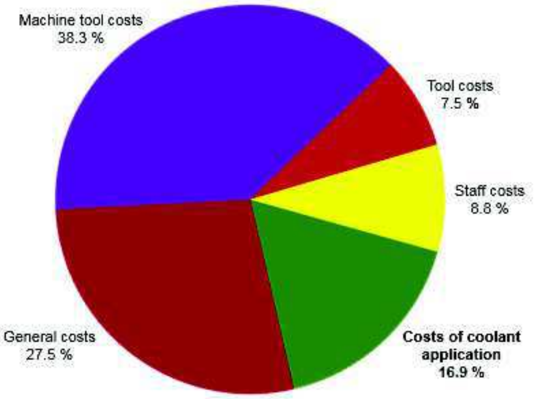

Figure 22. Manufacturing costs at the German automotive industry (Sarhan et al., 2012)

However, the production and dumping of lubricants also has a significant influence on the environment. To measure the overall environmental impact of a lubricant, the entire life cycle must be taken into account (Boyde, 2002). Miller et al. (2007) perform a life cycle assessment of common oil lubricants as they compare them with soybean based lubricants to evaluate the environmental advantage of bio-based lubricants. An aluminum rolling process is selected to collect data for the use phase. The results for the environmental impact of mineral oil lubricants can be seen in Figure 23. The impact is expressed in mass of emissions per mass of oil. The bars for each gas resemble the variability of the gathered data. The diagram shows the contributions of the different life cycle phases to the emissions of certain gases. For instance, methane is mainly produced during crude oil extraction and the disposal after usage is most responsible for carbon dioxide emissions (Miller et al., 2007).

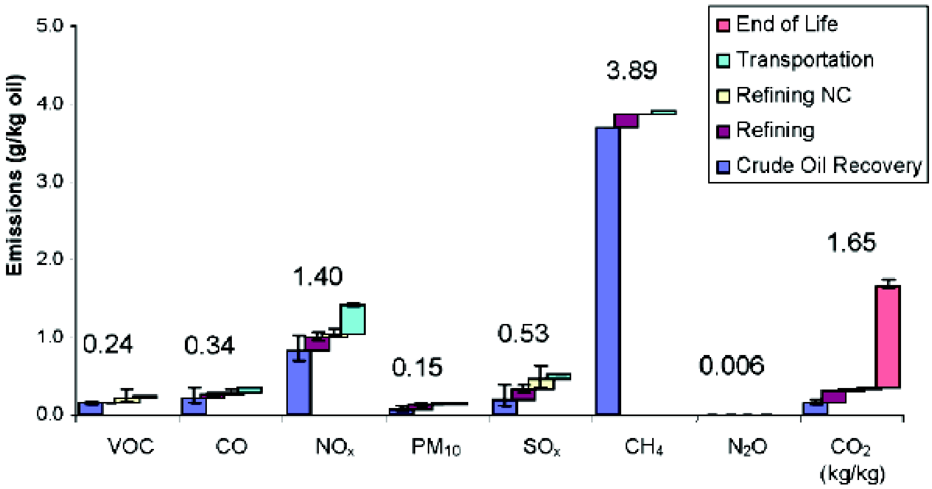

Figure 23. Environmental impact of mineral oil lubricants (Miller et al., 2007)

Because of the large environmental impact of lubricants, different approaches exist to find ways of lubrication that are more environmentally friendly. Those works mostly deal with investigating alternative lubricants (Sarhan et al., 2012) and lubrication strategies (Campatelli, 2009) to reduce the power and oil consumption of production machines.

2.6.2. Material Waste

A detailed work on material waste and the potential for its reduction and reuse is presented by Pacelli et al. (2015). Wastes are the non-value outputs of a manufacturing process. Two main types of material waste need to be distinguished in production systems: scrap and rejects. This differentiation is shown in Figure 24, using a blanking process as an example of a process in which both types of waste could result occur (Pacelli et al., 2015).

The amount of scrap produced in such a process is predictable since it depends on the design of the process itself. If a process stays the same, the exact same amount of scrap will be produced in each run of the process. The produced

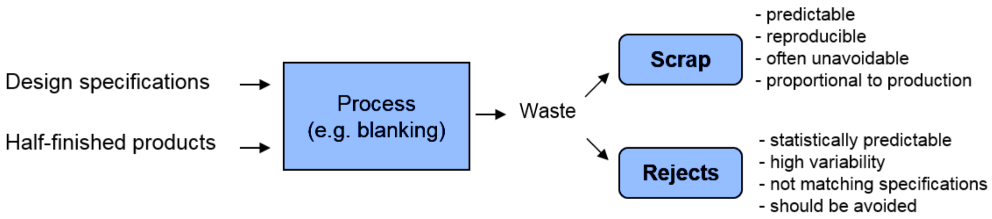

Figure 24. Material waste resulting from a blanking process (Pacelli et al., 2015)

scrap is therefore proportional to the production rate. Although there might be some potential to reduce scrap by redesigning the process, scrap can often not be avoided completely. Rejects, on the other hand, are defective products not matching the desired specifications. The amount of rejects resulting from a process can be predicted by a statistical analysis. However, their occurrence is determined by externalities and therefore is highly fluctuative. From a monetary perspective, the avoidance of rejects should be an objective of a manufacturing process (Pacelli et al., 2015).

Focusing on scrap, Pacelli et al. (2015) present a method for product designers to minimize and reuse scrap in industrial manufacturing. Scrap can be reduced in the design phase by adapting the geometrical and formal parameters of the product. However, in most cases the production of scrap cannot be avoided 100%. Some scrap always remains as a result from a manufacturing process, referred to as unavoidable scrap. The remaining scrap can eventually be reused. Case studies show that the reuse of scrap by applying creative design ideas can be less costly and more ecologically efficient than manufacturing a part in a traditional way (Pacelli et al., 2015).

Regardless, it must be pointed out that scrap remains to have an environmental impact even when being reused. This impact needs to be quantified when evaluating the sustainability of a production system.

2.7. Obstacles for Manufacturing Companies

Approaches on different levels to improve sustainability in manufacturing are shown in Section 2.3. But there are also obstacles that prevent companies from putting these approaches into practice. The question is which factors are causing these drawbacks. Jaffe and Stavins (1994) indicated that a gap exists between the measures and technologies existing for energy efficiency, and those that are implemented in companies. Furthermore, the existing approaches are economical, meaning that there must be other factors that impede their application (Jaffe and Stavins, 1994).

Obstacles, or barriers, for sustainability in manufacturing are any factors that prevent the implementation of energy-efficient measures or mitigate the propagation of these measures among manufacturing companies (Sorrell et al., 2004). Various works can be found that try to identify these obstacles, such as interviews conducted by Rohdin and Thollander (2006) in non-energy intensive manufacturing enterprises in Sweden. The observed barriers in their study are divided into four groups: economic non-market failure, economic market failure, behavioral, and organizational obstacles (Rohdin and Thollander, 2006). To get an overview of the works existing in literature, Chai and Yeo (2012) provided a broad literature review on barriers for energy efficiency. Analyzing different publications, a similar classification of obstacles is presented (Chai and Yeo, 2012). By combining the two approaches for a categorization of obstacles and examining the examples presented, barriers for sustainable manufacturing can be distinguished as shown in Table 8.

Market failures and institutional shortcomings are external factors and cannot be influenced by methods applied in a company itself. Changing people's behavior

Table 8. Classification of obstacles for sustainable manufacturing

Category	Example
Market failure	- Asymmetric infortmation - Unpriced energy costs
Institutional	- Lack of strict policies and legislation - Lack of government support
Behavioral	- Resistance to change
Organizational	- Other priorities than environmental issues - Lack of knowledge in sustainability and energy saving possibilities

requires knowledge in social sciences and is not to be further investigated in this work. Therefore, it is the organizational obstacles that impede the implementation of environmentally-friendly approaches in manufacturing companies. Looking further into this category, additional and more detailed examples for organizational obstacles are found as follows (Chai and Yeo, 2012) (Thiede et al., 2012):

1. Lack of metering capabilities prevents a transparent overview of the energy consumption of manufacturing equipment
2. Lack of financial resources to invest in sustainability
3. Lack of existing expertise in the company and missing resources to train personnel
4. Environmental benefits of measures might lead to decline in other performance factors
5. Approaches presented in scientific literature are difficult to be implemented in practice

Obstacle 1 - 3 depend on the resources available in a company. However, it is difficult to increase the amount of resources. Obstacles 4 and 5 result from the respective approach itself. Conflicts between environmental objectives and other performance indicators of the production system need to be identified. In a best-case scenario, a method might be able to align the different goals. Otherwise, a reasonable alternative trade off must be found.

2.8. Need for a Practical Method for Sustainable Routing

The reviewed literature shows that sustainability has not only become an important issue in society, but also in manufacturing. Emission regulations, climate change, and changes in consumer behavior are calling for a more environmentally-friendly way of manufacturing. Thus, the environmental impact of processes must also be considered in routing decisions. This calls for the development of a new approach for sustainable routing in manufacturing.

From the different presented methods in Section 2.3, it can be stated that a systems perspective is needed to make sustainable routing decisions. To assess the sustainability of a routing, evaluation techniques, like sustainable value stream mapping and life cycle assessment, can be applied. In this context, it is necessary to include the energy and material consumption of a routing in the analysis.

Furthermore, most existing approaches for sustainable manufacturing are not suited to be implemented into practice as they fail to overcome the obstacles mentioned in Section 2.7. Their application often requires resources that are not available or are just too complex for versatile real-world systems. For instance, transferring the utilization of complex algorithms into practice is often not possible and the required computation may not be feasible. Thus, a new method for sustainable routing needs to be practical in order to close the existing gap between literature and practice. It must be designed to consume less resources and to be applicable and accessible to companies.

3. Methodology

In this chapter, the methodology to develop a new approach for sustainable routing in manufacturing enterprises is presented. The method is designed to be used as guidance for manufacturing companies to make sustainable routing decisions. In order to create a practical method, a case study approach is chosen. For a specific case, routings are evaluated in terms of their sustainability. This way ensures that the derived method is suited for practical applications. The methodology of this study and the structure of this chapter are illustrated in Figure 25.

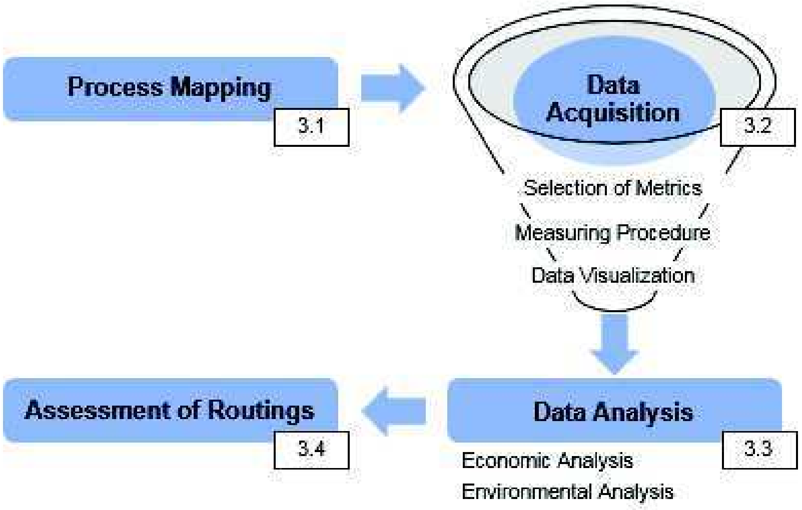

Figure 25. Methodology of the study

The first step within the case study is to map the processes that are involved in the production of a selected part. Different routings through which this part can be manufactured are identified. Following that, data for the processes is collected. The acquisition of the data requires a selection of metrics that display the sustainability of a process. The reasons for choosing the respective metrics and the procedures for measuring the needed data are explained. The data is presented in a sustainable value stream map. After all of the data for the investigated processes is collected, it is analyzed in order to derive performance indicators for the sustainable assessment of different routings. This includes an economic analysis as well as an environmental analysis of the process data. Finally, the process routings are compared with one another based on the determined performance indicators. Recommendations are made on how the investigated manufacturing system in the case study can be improved by making sustainable routing decisions. Based on this specific case, a new method for sustainable routing is derived that is generally applicable and scalable for manufacturing enterprises in different industries.

3.1. Process Mapping

At first, the basic conditions under which the case study is conducted need to be determined. Therefore, a company is selected which has a manufacturing system suitable for the scope of this study. The goals of the study are explained to the plant's management. All further steps of the case study are carried out as agreed upon with the company.

For the purpose of this study, one product is selected from the company's portfolio. However, the production of a whole product involves too many process steps. Investigating all of them is not feasible within this study. As the focus of the case study is discovering how sustainable routing decisions can be made in practice, looking at all steps in manufacturing a whole product is not necessary and does not contribute to the objective of the study. Therefore, just one part of the product and its manufacturing process are considered. This way, the resources available can be pooled to analyze the process routings in a more detailed manner. The requirement in choosing the respective part is that multiple routings are available to manufacture the part.

To identify all possible routings and to map the process, different options are discussed with the management. A chart is developed to illustrate the determined routings. To get a better understanding of the various possibilities, the process routings are also walked on the shop floor. A plant layout is used to create a spaghetti diagram that shows all of the routings on the shop floor.

3.2. Data Acquisition

In this Section, the procedure of gathering the data that characterizes the different processes and routings is explained. Therefore, appropriate metrics are selected to represent the sustainability of the processes. For each of those metrics, the measuring approach is described. Furthermore, the steps of data processing alongside the applied equations are given. In order to get an overview of the gathered data and to use it as the basis for further analyses, a method for the visualization of the data is also presented.

3.2.1. Selection of Metrics

Before data for the different processes can be collected, the metrics to be measured are determined. An example for possible metrics was shown in Section 2.4.1 in which Faulkner & Badurdeen (2014) selected certain metrics to develop a sustainable value stream map (Faulkner and Badurdeen, 2014). Their work and other works in literature that were reviewed in Chapter 2 are used to choose the metrics that are investigated in this study. Furthermore, Feng et. al (2010) pointed out that a metric to display the sustainability of a process must be easily measurable and significant for the overall objectives of an enterprise (Feng et al., 2010). These characteristics are also considered in order to identify adequate process metrics. A short description of the metrics selected for this study can be seen as follows:

- **Cycle time**

  Cycle time (C/T) is often defined differently when analyzing production systems (Hopp and Spearman, 2001). In this study, cycle time refers to the time a workstation requires to complete its processes. For routing decisions, the cycle time should be monitored to discover which processes are fastest. Furthermore, the cycle time is divided into the time that is needed for material handling steps (MH/T) and the actual processing time (P/T). This differentiation is made to distinguish idle and processing times of machines with regards to manufacturing a certain part. Additionally, the number of material handling steps (#MH) needs to be observed to examine how often a worker moves the part.

- **Changeover time**

  A changeover occurs when there is a change in the product or part processed on a certain machine. This means that the respective machine needs to be set up for the new product or part. The time required for this is referred to as changeover time (C/O). The changeover time is needed to know how much time it takes to set up the machine for a certain process.

- **Electrical energy consumption**

  As electrical energy is a significant and widely used input factor for manufacturing processes, the amount of electrical energy required to produce a part needs to be identified. As seen in Section 2.5.1, the power consumption of machines varies over time. Thus, the idle energy consumption and the energy consumed during processing are investigated in this study.

- **Compressed air consumption**

  According to the reviewed literature, compressed air is used for a large variety of purposes in manufacturing and is also a cost-intensive type of energy. Thus, the amount of compressed air in manufacturing a part must be measured. To identify the share of different process phases for the compressed air usage, a distinction between idle times and processing times is necessary. Furthermore, an approach must be designed to derive the resulting energy consumption from the compressed air usage.

- **Material usage**

  In manufacturing processes, raw material is transformed into the desired product. However, byproducts, like scrap, are also part of the process output and have a significant impact on the environment. To assess the material usage for producing a part, the amount of raw material used and the amount of scrap that results from processing a part are quantified in this study.

- **Lubrication oil consumption**

  In Section 2.6.1, it was pointed out that lubrication oils cause a significant proportion of costs in manufacturing and that their usage is associated with a high impact on the environment. For instance, the extraction and disposal of oil causes emissions of various greenhouse gases. Therefore, it must be quantified how much oil is used per manufactured part.

- **Water consumption**

  Faulkner & Badurdeen (2014) consider the process water consumed for manufacturing a product in their sustainable value stream map. The assessment of the water consumed for processing a part can be distinguished between the water that is actually lost after processing and water that is recycled for other processes in the factory through waste-water treatment (Faulkner and Badurdeen, 2014). In this study, a possible reuse of water through waste-water treatment is not considered. Therefore, only the actual volume of water that is needed to process a part is monitored.

- **Work environment**

  The work environment is selected as a metric to represent the social dimension of sustainability. When it comes to the work environment, the noise level in a factory is important. A high noise level can cause serious effects on the health of the employees (Faulkner and Badurdeen, 2014). For this reason, the noise level is chosen as a parameter to evaluate the work environment in the case study.

A summary of all metrics selected for this study classified by the three dimensions of sustainability is shown in Table 9. It must be noted that some of the metrics can be assigned to multiple dimensions. For instance, the amount of electrical energy consumed to produce a part is relevant in regards to both the economic and the environmental performance.

Table 9. Selected metrics classified by the dimensions of sustainability

Dimension	Metrics	
Economic	Cycle Time Electrical energy Material usage Water	Changeover time Compressed air Lubrication oil Consumables
Environmental	Electrical energy Material usage Water	Compressed air Lubrication oil
Societal	Work environment	

3.2.2. Measuring Procedure and Data Processing

The required data for the listed metrics is either gained from information that is already available in the company or it is directly measured on the shop floor. In the latter case, the measuring procedure is described. Furthermore, the way in which the measured data is prepared to be used for the purpose of this study is clarified. For instance, some of the data needs to be scaled for the manufacture of just one part. If calculations are necessary, the respective equations are provided and explained. The procedures for the different metrics are expounded as follows:

- **Time study**

  A time study is conducted to measure the cycle time for each workstation. This includes timing the material handling time and the actual processing time. The material handling time includes loading a machine with a work piece and taking out the part after processing. The number of material handlings by the respective operator is counted. Furthermore, the changeover time for each workstation is measured. The amount of time an operator needs to set up a machine for the investigated part is recorded. For most of the processes viewed, parts are produced in batch sizes. To get the time for just one part in a case like this, the times are measured for a whole batch and are then divided by the batch size according to Equation 1.

  $$\text{Time per part} = \frac{\text{Time per batch}}{\text{Batch size}} \tag{1}$$

- **Electrical energy consumption**

  The electrical energy consumed by each process is divided into the idle energy consumption and the processing energy consumption. According to Equation 2, the respective amount of consumed energy can be calculated by multiplying the average power consumption with the time period of energy consumption. Thus, the average power consumption during idle times and during processing times is measured for each process. To calculate the energy consumption, the measured values are then multiplied with the idle time and the processing time, respectively. These times were quantified in the time study.

$$\text{Electrical energy consumption} = \text{Avg. power consumption} \times \text{Time} \qquad (2)$$

- **Compressed air consumption**

  The amount of compressed air consumed per time is measured for each process. As in the case of electrical energy consumption, two measurements are taken for each process to distinguish between the idle state and the processing state of machines. The volume of air consumed in processing a part is calculated by multiplying the measured consumption rate with the respective time gathered during the time study. However, the compressor has to supply more compressed air to the system than the amount that is actually used. The reviewed literature indicates that there are significant losses through leaks in compressed air systems (Saidur et al., 2010). Thus, the volume of air consumed by a process is multiplied by a leakage factor to account for the additional volume that the compressor has to produce. An appropriate value for the leakage factor in the investigated case study is retrieved from the literature. To assess the energy consumption that is equivalent to the amount of air used, it is necessary to examine how much energy the compressor consumes in order to produce a certain volume of compressed air. This is referred to as generation efficiency. The generation efficiency of a compressor can be retrieved by measuring its power consumption for a certain supply rate of compressed air. By multiplying this factor with the volume of air supplied for a process, the amount of energy consumed due to the usage of compressed air can be identified. The calculation of the energy consumption is summarized in Equation 3.

$$\begin{aligned}\text{Energy consumption (CA)} = {} & \text{Consumption rate} \times \text{Time} \\ & \times \text{Leakage factor} \times \text{Generation efficiency} \qquad (3)\end{aligned}$$

- **Material usage**

  To measure the material usage in producing a part, the metal sheets used as raw material and the amount of scrap that remains after processing are weighed. If there is a batch process, both the total raw material used and the amount of scrap produced for the whole batch process are scaled and then divided by the batch size as seen in Equation 4.

  $$\text{Weight per part} = \frac{\text{Weight per batch}}{\text{Batch size}} \qquad (4)$$

- **Lubrication oil consumption**

  To identify how much oil is used to manufacture one part, an approach by Clarens et al. (2008) from the literature is adapted. In their work, the cutting fluid consumption of machines is investigated under the assumption that the machining time per year is constant for each machine. Given this, the time a machine uses one full tank can be calculated by multiplying the machining time with the time until an exchange is necessary. The tank capacity divided by this time then gives the amount of oil consumed per time. Finally, the oil consumption per part can be computed by multiplying the consumption per time with the process time of a part (Clarens et al., 2008). The whole calculation can be seen in Equation 5.

$$\text{Oil consumption} = \frac{\text{Tank capacity}}{\text{Machining time} \times \text{Usage period}} \times \text{Process time} \tag{5}$$

- **Water consumption**

  The volume of water used and the time period of usage for that volume are monitored for each machine. The water usage for production processes is calculated similar to the usage of oil in Equation 5. Thus, the water consumption per part can be determined according to Equation 6.

$$\text{Water consumption} = \frac{\text{Tank capacity}}{\text{Machining time} \times \text{Usage period}} \times \text{Process time} \tag{6}$$

- **Work environment**

  The assessment of the work environment is done by measuring the noise level in the factory. To compare different routings and machines with each other, the noise level is metered at each machine. To calculate the noise exposure of an operator, the time-weighted average sound level (TWA) can be used. However, if the noise level is assumed constant for an eight-hour shift, the TWA and the measured noise level have the same value. To account for ear protection, the noise reduction rating (NRR) is used. The NRR is subtracted from the TWA (OSHA Standard 1910.95, 2008). The final calculation of the noise exposure of an operator can be seen in Equation 7.

$$\text{Noise exposure} = \text{Average noise level} - \text{Noise reduction rating} \tag{7}$$

3.2.3. Data Visualization

To visualize the data, the technique of sustainable value stream mapping is applied. In Section 2.4.1, different approaches for green and sustainable value stream maps existing in literature were presented. Based on these methods, a new design for a sustainable VSM is developed which displays the metrics investigated in this study. A data box to visualize the collected data for each process is shown in Figure 26.

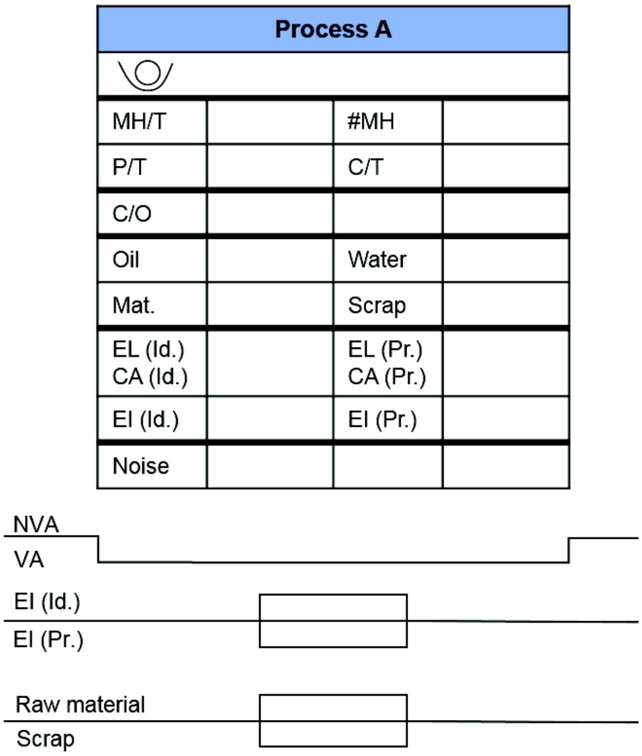

Figure 26. Value stream map data box

The data box contains all the data gathered as described in the previous section. These include the different times measured during the time study, the oil and water consumption of machines, the material usage, the energy consumed due to electrical energy (EL) and compressed air usage (CA), and the noise exposure.

The energy consumption is displayed for idle times (Id.) and processing times (Pr.). The energy intensity (EI) is the sum of the two measured energy carriers, electricity and compressed air, and shows the total energy consumption of a process. Below the data box, three diagrams illustrate the most important information. The diagrams display the following:

1. The value-adding (VA) and non value-adding (NVA) cycle times
2. The energy intensity during idle and processing phases
3. The raw material usage for the process and the amount of scrap created

Furthermore, the designed sustainable VSM contains all aspects that can be seen in a traditional VSM, such as data for inventory between processes and the information flow to control production. By giving an overview of the gathered data, the sustainable VSM can be used as a basis for further analyses of the different processes.

3.3. Data Analysis

In this Section, the procedure of analyzing the gathered process data is presented. Economic and environmental performance indicators for each process are identified to be used as decision criteria for a sustainable choice of possible process routings. In terms of the social dimension, only one metric, the noise level of processes, is considered. Therefore, a further analysis of the data for this one metric and a definition of a societal performance indicator are not necessary for decision making. For the economic and environmental analyses, the required steps in deriving the performance indicators are explained. Mathematical calculations are expounded and the applied equations are given. If software is used to support the data analysis, the functionality of the respective software is described.

3.3.1. Economic Analysis

The economic analysis of the data involves calculating the costs for each process that result from manufacturing a part. To derive the costs from the process data, different cost categories are distinguished. Following, the calculations for each cost category are explained:

- **Labor costs**

  To assess the costs for labor in manufacturing one part, the average labor costs are identified. These costs describe the average amount of money paid per hour for labor in the investigated plant. To calculate the labor costs for each process, this cost factor is multiplied by the cycle time of the respective process. The computation is displayed in Equation 8.

  $$\text{Labor costs} = \text{Average costs per hour} \times \text{Cycle time} \tag{8}$$

- **Energy costs**

  Two energy carriers, electrical energy and compressed air, were selected as metrics in this study and are used to examine the energy costs of processes. To identify the share of different process phases for the energy costs, a distinction between costs that occur during machine idle times and costs that result from the actual processing is made. The price per kWh that the company pays for electricity is used as a cost factor. This factor is multiplied by the total electrical energy that a process needs to manufacture one part as seen in Equation 9. This includes directly consumed electrical energy as well as electricity used to provide compressed air for the respective process.

  $$\text{Energy costs} = \text{Costs per kWh} \times \text{Total energy consumption} \tag{9}$$

- **Material costs**

  To quantify the material costs per part, the raw material costs per lbs are derived from the purchasing prices of the sheet metal. For some of the investigated routings, various sizes of sheets are purchased which leads to different raw material cost factors. The cost factor is multiplied by the weight of the raw material used to calculate the total raw material costs. Furthermore, the scrap remaining after a process which can be sold to recycling companies must be considered. To quantify the resulting revenue, the company's selling price for scrap is used. The scrap price per lbs is multiplied with the scrap weight and subtracted from the material costs. Equation 10 shows the calculation for the material costs.

$$\begin{aligned}\text{Material costs} = {} & \text{Costs per lbs} \times \text{Raw material weight} \\ & - \text{Scrap price per lbs} \times \text{Scrap weight} \qquad (10)\end{aligned}$$

- **Lubrication oil costs**

  The costs for the lubrication of production machines need to be assigned to the processing of one part. Different machines use different types of lubrication oils which can lead to different costs per gallon. These cost factors must be identified for each process. The lubrication oil costs are then calculated by multiplying the cost factor per gallon with the volume of oil used in processing one part according to Equation 11.

$$\text{Lubrication oil costs} = \text{Costs per gal} \times \text{Oil consumed per part} \qquad (11)$$

- **Water costs**

  For the cooling of machines, often certain types of purified water are required which results in extra cost. Thus, the costs for water used for processing a part must be considered in routing decisions. The company purchases purified water for certain machines on a regular basis. From these purchasing prices, the costs per gallon are derived and then multiplied with the volume of water consumed per part as seen in Equation 12.

$$\text{Water costs} = \text{Costs per gal} \times \text{Water consumed per part} \tag{12}$$

- **Consumables costs**

  Some production machines need certain consumables for their operation. As these consumables can cause significant costs, they need to be included in the economic analysis of manufacturing processes. To derive the costs of consumables for producing one part, Equation 5 for the calculation of oil consumption is adapted. The costs for consumables per year for a process are divided by the machining time per year and then multiplied with the process time of a part on the respective machine. The computation for the costs for consumables per part can be seen in Equation 13.

$$\text{Consumables costs} = \frac{\text{Consumables costs per year}}{\text{Machining time per year}} \times \text{Process time} \tag{13}$$

Finally, the total costs caused by each process are calculated as the sum of the described cost categories according to Equation 14. The total costs of processes are used as a basis to evaluate the economic performance of possible process routings.

$$\begin{aligned}\text{Total cost per process} = {} & \text{Labor Cost} + \text{Energy cost} + \text{Material cost} \\ & + \text{Lubrication oil cost} + \text{Water cost} + \text{Consumables cost}\end{aligned} \tag{14}$$

3.3.2. Environmental Analysis

The objective of an environmental analysis of the gathered data is to assess the environmental impact of the investigated processes. For this purpose, the method of life cycle assessment is applied. The software Umberto NXT LCA is used to support the conduction of a life cycle assessment. The software enables a creation of a visual model of a product system, so that all flows contributing to the manufacture of a product become visible. For the inventory analysis, the database ecoinvent is used which provides more that 10,000 data sets of various factors, such as energy supply or the production of metal materials. Furthermore, multiple evaluation methods for the assessment of the environmental impact can be applied within the software.

In the literature reviewed in Section 2.4.2, the four required steps for the conduction of a life cycle assessment are explained. These steps include setting the goal and scope of the method for the respective study, an inventory analysis of the relevant data, an assessment of the environmental impact, and an interpretation of the results. The life cycle assessment in this study follows this general procedure. Thus, the methodology of the conducted life cycle analysis is described based on these four steps:

1. **Goal and scope**

   The objective of the life cycle assessment is to examine the environmental impact of all processes that are potentially involved in the manufacture of the part investigated in the case study. The overall goal is to compare different possible process routings to produce a part, in terms of sustainability. To assess the sustainability of routings, the environmental impact of routings is of particular importance. In this context, information is necessary regarding the environmental impact of the processes that together create those routings. One unit of the examined part is used as the functional unit for the life cycle assessment. This means that all calculations for the inventory data are based on one unit of the part. Using the same functional unit for all processes enables a comparison of the results for the processes and overall of the different process routings. Furthermore, the whole life cycle of the part is not viewed. As the overall objective is to compare multiple potential manufacturing routings with one another, the main focus is on the manufacturing phase of the part. However, some of the processes use different raw materials, so the production of raw materials and its environmental impact also need to be considered. All other downstream life cycle phases are excluded from the analysis.

2. **Inventory analysis**

   In the inventory analysis, all relevant input and output flows for the investigated processes are quantified. These include material flows (raw materials and scrap), energy flows, lubrication oil flows, and water flows. The data for these flows is acquired beforehand as described in Section 3.2.2. To evaluate the environmental impact of the different flows, data characterizing the supply processes of these flows is also needed. For this purpose, generic data from adequate data sets is used. If there is no appropriate data available within the database ecoinvent, data sets from other sources must be retrieved. All flows are implemented into a petri net within the software. The different elements that can occur in such a petri net are represented by the icons shown in Figure 27. Processes, inputs, and outputs each have their own icon. Two processes can be connected via a special "connection" icon. All flows within the petri net are illustrated with arrows. A special purple arrow, the so-called ”manual flow”, determines the amount of product flow on which all calculations are based.

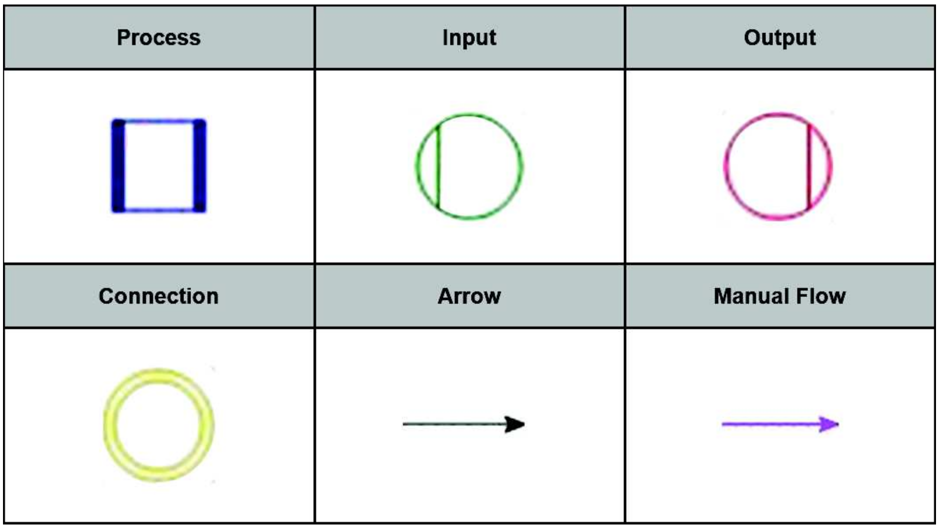

Figure 27. Icons within Umberto NXT LCA

3. **Impact Assessment**

   In Section 2.4.2, different environmental impact categories have been presented. All these impact categories are selected within the software for the impact assessment. However, the impacts for some categories might only be marginal and can therefore be neglected for further interpretations. The software offers different evaluation methods to quantify the environmental impact. For this study, the ReCiPe midpoint method is selected to assess the environmental impact of processes.

4. **Interpretation**

   The results of the life cycle assessment for the chosen impact categories are displayed for every process. From this information, the environmental impact of the different possible process routings can be derived. Thus, the results are used as a basis for evaluating the environmental impact of potential routings.

3.4. Assessment of Process Routings

In order to make sustainable routing decisions within the case study environment, the identified routings are compared with one another in terms of their economic and environmental performance. For this purpose, the results of the economic and environmental analysis of the process data are used.

To compare the economic performances of the different process routings with one another, the costs for all processes involved in a routing are summed up. This way, the total cost of producing a part via a certain routing can be calculated. The environmental impact of a routing can be acquired directly from the software Umberto NXT LCA. Therefore, the models used for the life cycle assessment of the processes are put together to create a specific model for each routing that considers solely the processes of that routing. The software provides detailed information about the selected environmental impact categories for manufacturing a part via a certain routing.

The most cost-efficient way of producing the investigated part is retrieved by comparing the costs of the potential routings with one another. The environmental impacts of the process routings indicate the most environmentally-friendly option of manufacturing the part. It is possible that the two comparisons do not favor the same routing. This means that a routing could be the most cost-efficient one without having the least environmental impact. In this case, a trade off between the two dimensions is made by setting preferences on the performance indicators. Based on the results of the comparisons of routings, recommendations for routing decisions are given to improve the current situation in the investigated company. To show how these changes would help the manufacturing system to become more sustainable, the benefits of the recommendations are pointed out.

It must be noted that this study just considers one specific case. The circumstances for routing decisions vary among different companies and industries. For instance, other metrics than those investigated in this study may be relevant for assessing the environmental impact in certain industries. However, a basic conceptual method to approach sustainable routing in manufacturing companies can be created resulting from this case study. Therefore, all of the required steps for evaluating various process routings in terms of their sustainability are registered and generalized to be scalable for multiple applications. This way, a general method is developed that can be used as guidance by manufacturing companies across different industries.

4. Case Study Data

The results of the acquisition and the analysis of data during the conduction of the case study are presented in this chapter. First, the case study environment and the part selected for the study are described in Section 4.1. This includes the identification and graphical presentation of the various possible process routings to manufacture the respective part. In Section 4.2, the measurement results for the chosen process metrics are displayed. Examples for the preparation of the data are given for each metric. An overview of all the gathered process data is provided in a sustainable value stream map. The results of the economic analysis of the data are expounded in a cost evaluation in Section 4.3 alongside a calculation example for each cost category. In Section 4.4 the outcomes of the conducted life cycle assessment are shown to assess the environmental impact of the processes. This includes extracts from the software used for the analysis.

4.1. Process Routings

The company chosen for the case study operates globally in the thermal management industry. It produces a variety of different heat transfer units for a wide spectrum of customers. A medium-sized plant of the company is investigated in which the employees work eight hours per day in a one shift system. A certain size of one of the product families manufactured in the respective plant is picked for this study. However, the case study just focuses on the front case of that product. The front case is selected as the part to be examined, because various routings can be used to produce this part. A technical drawing of the front case can be seen in Figure 28.

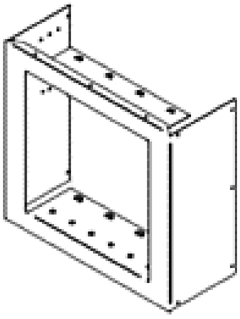

Figure 28. Part investigated in the case study

The results of mapping the process for the part are illustrated schematically in Figure 29 showing all processes included in the potential routings to produce the part.

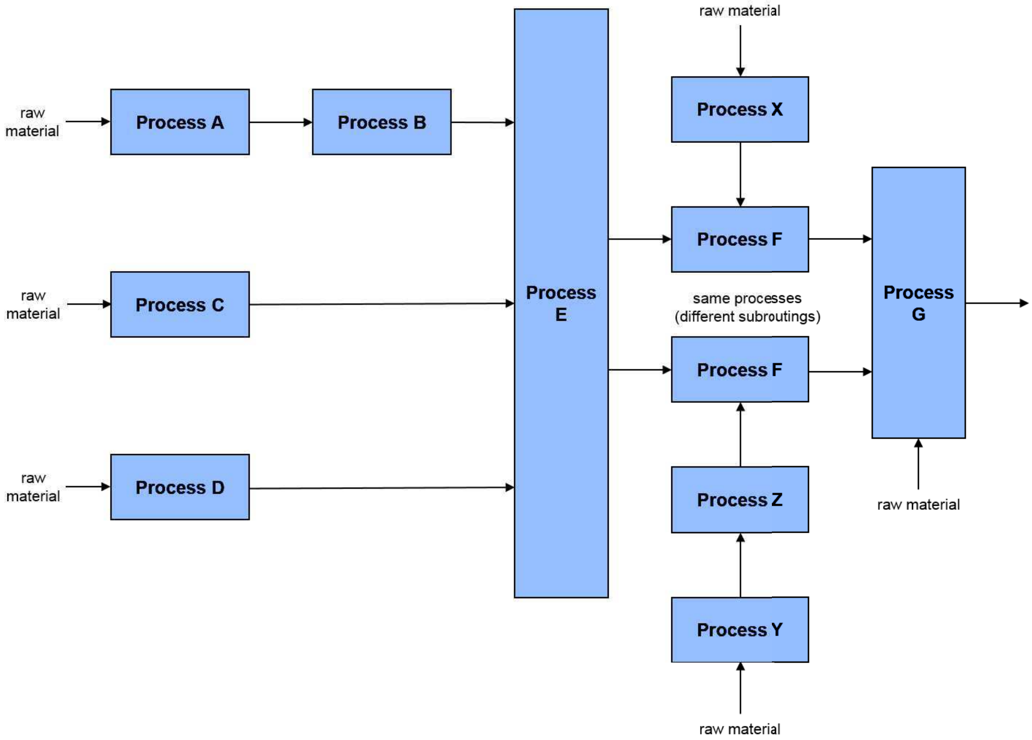

Figure 29. Process map with potential routings

The processes A, C, and D each represent a starting point of three possible main routings. Process E, F and G are performed in every routing. However, process F occurs twice in the figure, because there are two different sub-routings available to produce additional components required for process F. Table 10 displays the three main routings and the two sub-routings.

Table 10. Main routings and subroutings

Routing	**Processes**				
main routings	A	B	E	F	G
	C		E	F	G
	D		E	F	G
sub- routings	X				
	Y	Z			

With three main routings and two sub-routings available, there are six possible routings. All potential routings are summarized in Table 11 alongside the processes that they contain. It must be noted that routing 3 is by far the most frequently used routing in the investigated company.

Table 11. Possible process routings

Routing	**Processes**									
1	A	B			E	X			F	G
2			C		E	X			F	G
3				D	E	X			F	G
4	A	B			E		Y	Z	F	G
5			C		E		Y	Z	F	G
6				D	E		Y	Z	F	G

The path that a part takes on the shop floor when a certain routing is used is also observed for each routing. With this data and a layout of the shop floor, a spaghetti diagram is created which illustrates the movements for the different routings throughout the factory. The diagram can be seen in Figure 30. The three main routings are marked red, green, and blue. The two sub-routings are displayed by purple and yellow dotted lines.

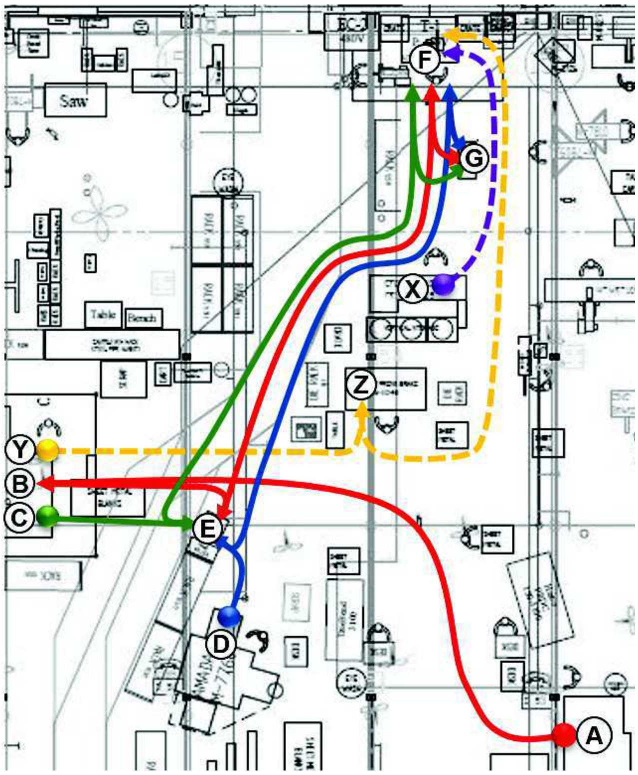

Figure 30. Process map with potential routings

4.2. Measurement Results

In this section, the results of data collected during the case study are presented. The data gathered for the metrics selected in Section 3.2.1 is shown in Section 4.2.1. This includes a short description of the measurement procedure and the processing of the data. Based on these measurements, a sustainable value stream map is created in Section 4.2.2 to get a joint overview of the collected process data.

4.2.1. Process Metrics

Data measurements for the metrics are taken for each process using the approaches explained in Section 3.2. It must be noted that not every metric can be quantified for every process. For instance, not all processes need lubrication oil or consume water. Thus, data for a certain metric is only gathered if it is appropriate for the respective process. Following, the results of the data collection are presented. The measuring circumstances are explained briefly for each metric. If calculations are necessary for data preparation, the application of the equations presented in Section 3.2.2 is displayed for one exemplary process.

- **Time study**

  Using the measuring procedure described in Section 3.2.2, each process is monitored with a stop watch to measure the time for material handling, the processing time, and the changeover time. The cycle time is calculated as the sum of material handling time and the processing time. If an operator moves the part, this is considered as a material handling step. The number of those steps is counted for each process. If the process is a batch process, Equation 1 is employed to calculate the respective times per part. An example for the processing time of process A with a batch size of four parts can be seen in Equation 15.

  $$\text{Processing time per part} = \frac{300\text{ s}}{4} = 75\text{ s} \tag{15}$$

  The results of the time study for all processes are summarized in Table 12. The material handling time, the processing time, and the cycle time are given in seconds while the changeover time is displayed in minutes. It stands out that the cycle time of process D exceeds the cycle times of all other processes by about one minute. Furthermore, process D has the longest changeover time with 10:51 min. For process X, ten material handling steps are required as two components are produced and four different punch operations are conducted separately from one another for each component.

Table 12. Results of the time study

Process	**#MH**	**MH/T [s]**	**P/T [s]**	**C/T [s]**	**C/O [min]**
A	2	46	75	121	03:58
B	2	17	38	55	05:04
C	2	25	97	122	04:35
D	2	43	138	181	10:51
E	1	2	52	54	00:25
F	1	2	103	105	00:02
G	1	2	85	87	00:00
X	10	64	12	76	01:39
Y	2	8	36	44	02:29
Z	2	2	54	56	03:08

- **Electrical energy consumption**

  In the examined plant, no resources are available to implement an automated monitoring of the energy consumption of machines as suggested in the literature. A simple power meter is used to measure the power consumption of processes. During material handling steps, machines are in idle mode. In this time period, the idle power consumption of machines is metered. The power consumption for processing is measured while a machine performs operations on the part. According to Equation 2, the energy consumption is calculated by multiplying the power consumption with the appropriate time. The computation for the electrical energy consumption during process A is shown in Equation 16.

$$\text{Energy consumption} = 19.3\ \text{kW} \times 75\ \text{s} \times \frac{1\ \text{h}}{3600\ \text{s}} = 402\ \text{Wh} \qquad (16)$$

  All values for the power and energy consumption can be seen in Table 13. Power values are given in kW and energy values in Wh. Process G is performed completely manually without any electrical power consumption and therefore does not consume any energy.

Table 13. Electrical energy consumption data

Process	**Power idle [kW]**	**Power proc. [kW]**	**Energy idle [Wh]**	**Energy proc. [Wh]**
A	10.8	19.3	138	402.08
B	6.7	15.8	31.64	166.78
C	6.7	15.8	46.53	425.72
D	4.9	10.7	58.53	410.17
E	3.2	6.2	1.78	89.56
F	0.01	9.6	0.0061	274.67
G	-	-	-	-
X	5.6	8.9	99.56	29.67
Y	6.7	15.8	14.89	158
Z	15.5	18.8	8.61	282

Figure 31 illustrates the consumption of electrical energy of processes during both idle and processing times. In the diagram, it can be seen that processes A, C, and D consume the most electrical energy during processing a part. A relatively high amount of energy is used by process A during the idle phase. For process X, the energy consumption during idle times even exceeds the energy consumed for processing. The reason for this is the long material handling time of process X.

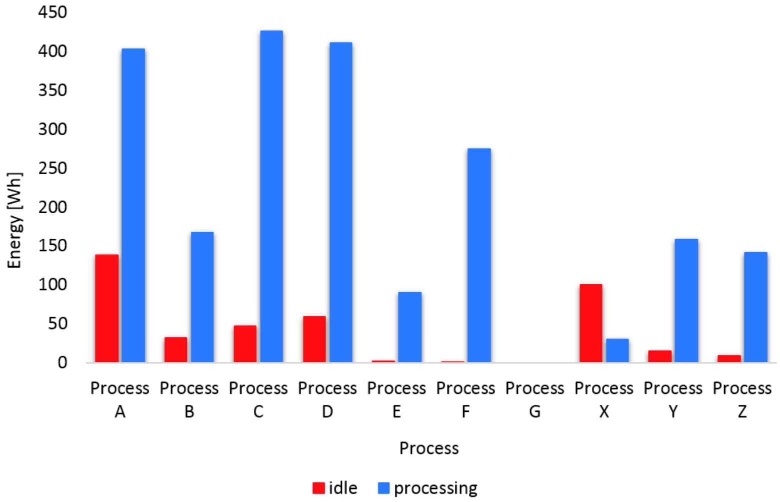

Figure 31. Electrical energy consumption of processes

- **Compressed air consumption**

  A flowmeter is used to measure the consumption rate of compressed air for each process. The meter clamps onto the pipe with two sensors reaching into the pipe. A picture of the meter can be seen in Figure 32. The flow rate is displayed in standard cubic feet per minute (scfm) which is a dimesion adjusted to normalized conditions of pressure and temperature.

Figure 32. Compressed air flowmeter (CDI Meters, Inc. , 2017)

  Measurements for the consumption rate during idle times and processing times are found in a way similar to the electrical energy consumption. The consumed amount of compressed air by a process is calculated as explained in Section 3.2.2. To account for leakage losses in the compressed air system, a leakage factor is determined. A leakage rate of 20% can be assumed as a usual loss rate in industrial manufacturing facilities (Saidur et al., 2010). Thus, the volume of air used by a process is multiplied with a factor of 1.2. To identify the generation efficiency of the compressor which shows how much energy is required to supply one standard cubic feet (scf) of compressed air, the meter is also installed at a location directly after the compressor in the pipe system. The power consumption of the compressor for a certain supply rate is provided by the compressor itself. Given these parameters, the generation efficiency of the compressor equals 3.4 Wh/scf. According to Equation 3, the energy consumption due to compressed air usage of a process is calculated by multiplying the air consumption with the leakage factor and the generation efficiency. An example for the calculation for process B during the processing phase can be seen in Equation 17.

$$\text{Energy consumption (CA)} = 6.3\text{ scfm} \times 38\text{ s} \times \frac{1\text{ min}}{60\text{ s}} \times 1.2 \times 3.4\text{ Wh/scf} = 16.28\text{ Wh} \quad (17)$$

Table 14 displays the air consumption in scf and the resulting energy consumption in Wh of each process for idle and processing phases. The processes A, G, and Z do not require any compressed air for their operations.

Table 14. Compressed air usage data

Process	Air usage idle [scf]	Air usage proc. [scf]	Energy idle [Wh]	Energy proc. [Wh]
A	-	-	-	-
B	0.028	3.99	0.12	16.28
C	0.042	10.185	0.17	41.55
D	7.834	66.7	32.16	272.14
E	0.00017	0.087	0.0068	0.35
F	0.0067	4.64	0.027	18.91
G	-	-	-	-
X	1.92	1.1	7.83	4.48
Y	0.013	3.78	0.054	15.42
Z	-	-	-	-

An illustration of the energy consumption of processes due to compressed air usage can be seen in Figure 33. It can be observed that process D uses a high amount of compressed air, and therefore energy, in producing one part. In fact, process D consumes more energy due to compressed air than all other processes combined. A potential reason for this observation may be that the machine used for process D is old, so that there may be leaks within the machine beyond the assumed leakage rate in the pipe system.

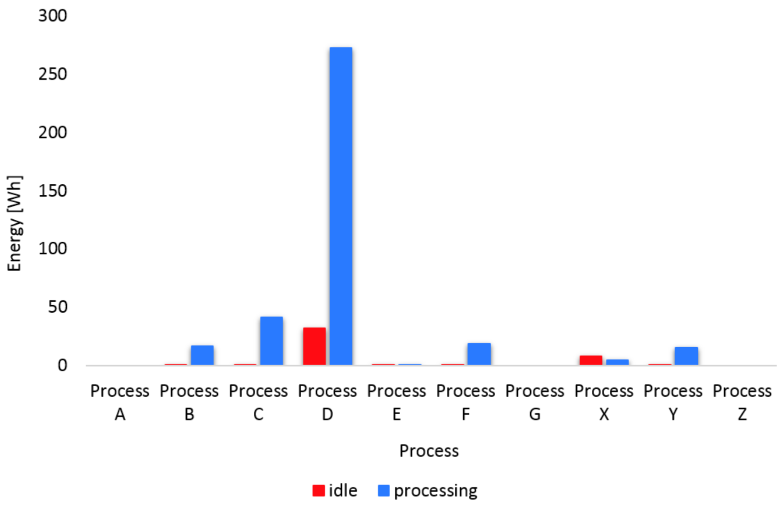

Figure 33. Energy consumption of processes due to compressed air usage

- **Energy consumption**

  Given the data for electrical energy consumption and the energy consumption due to compressed air usage, the total energy consumption of each process is calculated as the sum of these two metrics. Table 15 displays the energy intensity in Wh for each process. With 772.99 Wh, process D is the most energy intensive process. Processes A and C also consume a relatively high amount of energy. Process A is especially energy intensive during idle times.

Table 15. Energy consumption of processes

Process	**EI idle [Wh]**	**EI proc. [Wh]**	**EI total [Wh]**
A	138	402.08	540.08
B	31.75	183.06	214.81
C	46.7	467.28	513.98
D	90.69	682.3	772.99
E	1.78	89.91	91.69
F	0.033	293.58	293.61
G	-	-	-
X	107.39	34.15	141.54
Y	14.94	173.42	188.36
Z	8.61	282	290.61

In Figure 34, the contributions of the two investigated energy carriers to the total energy consumption during idle times and processing times are illustrated. For most processes, the share of compressed air is relatively small. However, in the case of process D the energy consumption due to compressed air usage accounts for about 40% of the total energy consumption. Furthermore, the idle energy consumption of process F is mostly due to compressed air usage. This observation is caused by the low electrical energy consumption of process F during idle phases and has not much significance, since the absolute values are very small as well.

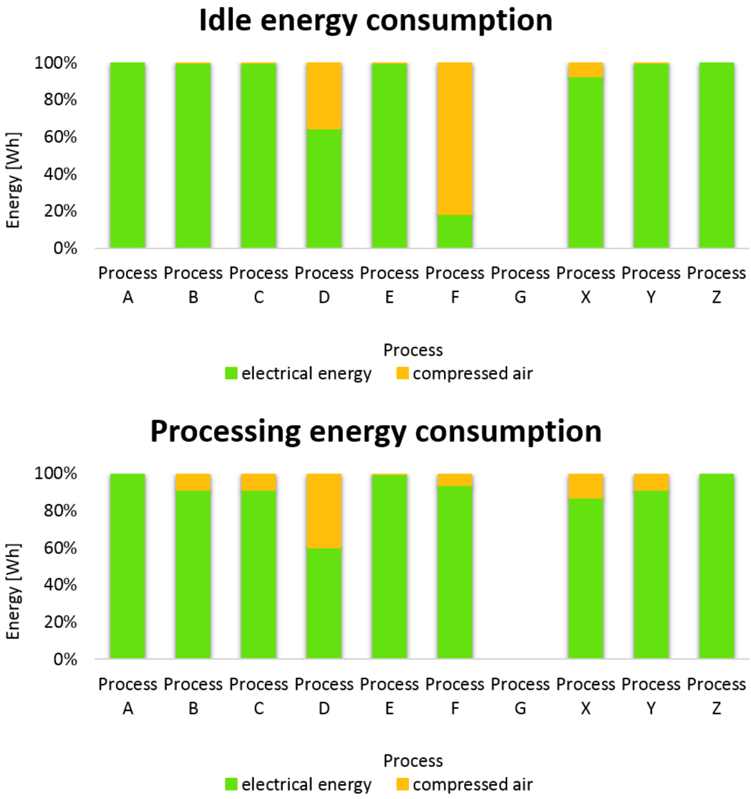

Figure 34. Contributions of energy carriers

- **Material usage**

The amount of raw material used in a process and the amount of scrap created are weighed using a scale which is available in the plant. For batch processes, the raw material and scrap per part are derived using Equation 4. For instance, the calculation for the scrap which remains after process A can be seen in Equation 18.

$$\text{Scrap weight} = \frac{11.68 \text{ lbs}}{4} = 2.92 \text{ lbs} \tag{18}$$

Table 16 shows the gathered material data in lbs for each process. It must be noted that not all processes use raw material or create scrap. Furthermore, the percentage of material usage for each process is displayed. Processes A, C, and D, which each occur in one of the main routings, have about the same material usage. Processes X and Y are options to produce an additional component for the investigated part. Regarding this case, the material usage of process X is about 15 % higher than the material usage of process Y.

Table 16. Material usage data

Process	**Raw material [lbs]**	**Scrap [lbs]**	**Material usage [%]**
A	10.52	2.92	72.24
B	-	-	-
C	10.52	2.92	72.24
D	10.55	2.95	72.04
E	-	-	-
F	-	-	-
G	-	-	-
X	1.9	0.9	52.63
Y	2.72	1.72	36.76
Z	-	-	-

- **Lubrication oil consumption**

  The company replaces the lubrication oils for the different machines regularly. The capacity of the oil tanks and the time period of usage are gained from the company's maintenance department. The oil consumption per part can then be calculated as explained in Section 3.2.2 by using Equation 5. A machining time of 2000 hours per year is assumed. As process A does not use any oil, a sample computation is shown for process B in Equation 19.

$$\text{Oil consumption per part} = \frac{33\ \text{gal}}{2000\ \text{h/yr} \times 1\ \text{yr}} \times 38\ \text{s} \times \frac{1\ \text{h}}{3600\ \text{s}} = 0.00017\ \text{gal} \quad (19)$$

The results for the oil consumption per part of each process can be seen in Table 17. As the oil usage is broken down for the manufacture of just one part, the displayed values are relatively small.

Table 17. Lubrication oil data

Process	**Oil consumption [gal]**
A	0
B	0.00017
C	0.00044
D	0.000096
E	0.000072
F	0
G	0
X	0.000017
Y	0.000165
Z	0.00011

- **Water consumption**

  When investigating the water consumption of processes, it is observed that only process A uses deionized water for cooling purposes. The water is stored in a drum that fits 55 gallons and is replaced six times per year. Equivalent to the oil consumption per part, the water consumption per part of process A is calculated as shown in Equation 20.

$$\text{Water consumption per part} = \frac{55 \text{ gal}}{2000 \text{ h/yr} \times 0.167 \text{ yr}} \times 75 \text{ s} \times \frac{1 \text{ h}}{3600 \text{ s}} = 0.0034 \text{ gal} \quad (20)$$

- **Work environment**

  To record the noise level associated with a process, the measurements are taken at the position of the machine operator for each process. A ten-minute average noise level is taken as a measurement value to account for potential variations in the noise level. The NRR for the ear protection used in the investigated company can be seen on the package. An NRR of 32 is derived. Finally, the noise exposure for an operator is calculated using Equation 7. The measured noise level and the final noise exposure in dB of each process are displayed in Table 18. The values for the noise level of the different processes lay in a small range. Under consideration of ear protection, none of the noise exposure values can be seen as a threat for the health of an operator. Thus, the measured noise level data is not used for further analysis and decision making.

Table 18. Results of noise level measurements

Process	**Noise level [dB]**	**Noise exposure [dB]**
A	73	41
B	77	45
C	77	45
D	75	43
E	73	41
F	72	40
G	72	40
X	73	41
Y	72	40
Z	73	41

4.2.2. Creation of a Sustainable Value Stream Map

The sustainable value stream map to display the collected process data is developed based on the process map shown in Figure 29. For each process in this map, a data box, as presented in Figure 26, is provided. The data boxes are filled with the gathered data for the processes. As described in Section 3.2.3, the most important information is also shown in respective diagrams below the data boxes. Information about inventory is gained from the plant's management and added to the value stream. Furthermore, the information flow within the plant to control the production is illustrated using dotted arrows. The sustainable value stream map for the conducted case study can be seen in Figure 35.

The customer for the investigated part is the assembly of the plant where the front case and other parts are put together to create the final product. The sustainable VSM shows all the potential routings including the two subroutings to manufacture the additional component. Thus, it must be noted that some of the WIP between the processes which is shown in the map only occurs if a certain routing is chosen. It stands out that there is the same amount of raw material in stock for the processes A and C, because both processes use the same metal sheets as raw material. The production system is organized according to a daily schedule given out by the production control.

The sustainable VSM gives the case study company an overview of its different processes and supports the management in understanding the relevant flows within the production system. In addition to a traditional value stream map, information about the energy consumption, the compressed air usage, and the material usage of processes is included to display a more complete picture of the performance of processes. Given this information, the company can use the tool to identify potential economic and environmental improvements of processes.

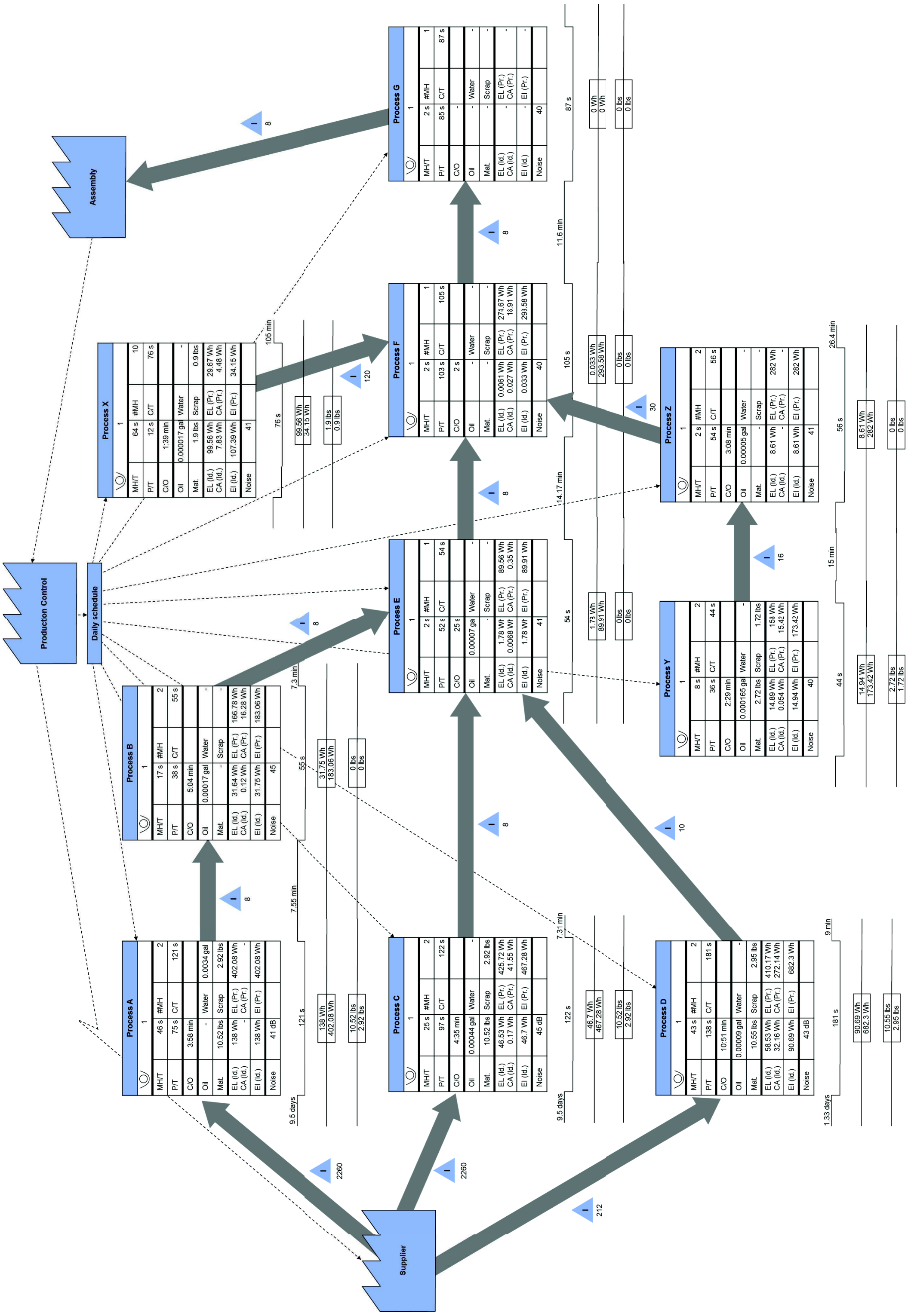

Figure 35. Sustainable value stream map

4.3. Cost Evaluation

The results of the economic analysis of the process data are the costs that each process causes in manufacturing one part. The costs for the cost categories defined in Section 3.3.1 are calculated for each process and finally summed up to identify the total process costs. This procedure can be seen as follows:

- **Labor costs**

  As more employees than just the machine operator are involved in the production of a product, an average labor cost factor of $42.73 per hour is gathered from the plant management and used for the calculations. According to Equation 8, this cost factor is multiplied by the cycle time of each process. An example for the computation for process A can be seen in Equation 21.

$$\text{Labor costs} = 42.73\ \$/\text{h} \times 121\ \text{s} \times \frac{1\ \text{h}}{3600\ \text{s}} = 1.44\ \$ \tag{21}$$

  The labor costs of each process are summarized in Table 19. Process D has the longest cycle time and therefore causes the highest labor costs.

Table 19. Labor costs of processes

Process	Labor costs [$]
A	1.44
B	0.65
C	1.45
D	2.15
E	0.64
F	1.25
G	1.03
X	0.90
Y	0.52
Z	0.66

- **Energy costs**

From the company's electricity bill a unit cost of 0.171 \$/kWh is retrieved. According to Equation 9, this cost factor is multiplied by the total energy consumption of a process to calculate the energy costs of a process. It is divided by energy costs that result from machine idle times and energy costs that result from the actual processing operations. An example for the calculation of the energy costs caused by process A during processing a part can be seen in Equation 22.

$$\text{Energy costs} = 0.171\ \$/\text{kWh} \times 0.402\ \text{kWh} = 0.069\ \$ \tag{22}$$

The idle energy costs, the processing energy costs, and the total energy costs of all processes are displayed in Table 20. Process D accounts for the highest energy costs while process E causes only marginal energy costs.

Table 20. Energy costs of processes

Process	**Energy costs idle [\$]**	**Energy costs proc. [\$]**	**Energy costs total [\$]**
A	0.024	0.069	0.093
B	0.005	0.031	0.036
C	0.008	0.079	0.087
D	0.016	0.117	0.133
E	0.0003	0.015	0.0153
F	0.000006	0.05	0.05
G	0	0	0
X	0.018	0.006	0.024
Y	0.002	0.03	0.032
Z	0.0015	0.048	0.0495

In Figure 36, the share of idle energy costs and processing energy costs of each process are illustrated. It stands out that the idle energy costs of process X account for over 70 % of the process' total energy costs. For all other processes, the major share of the energy costs is caused during processing times.

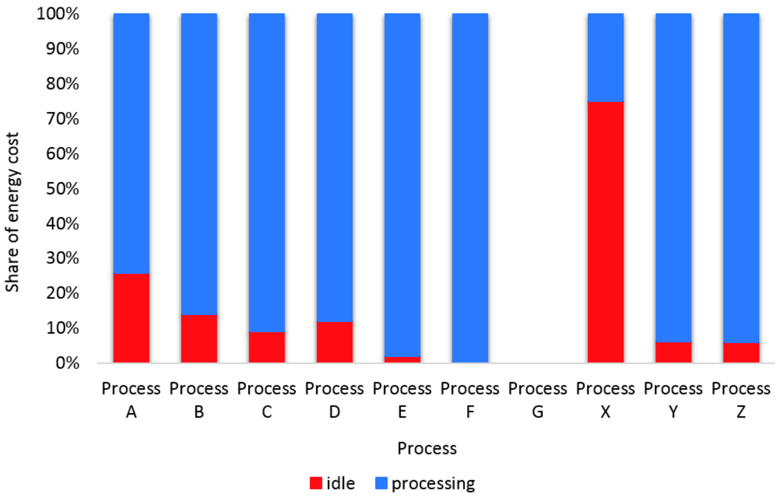

Figure 36. Share of idle and processing energy costs

- **Material costs**

  The prices per lbs for the different metal sheets and coils used as raw material for the processes are gained from the plant's purchasing department. To account for the revenue earned by selling the remaining scrap after a process, the selling price for scrap is identified as 7 ct/lbs. The final calculation of the material costs for each process is done according to Equation 10. The values displayed in Table 16 for the raw material weight and the scrap weight are used for the computation. For instance, the material costs for process A can be determined as shown in Equation 23.

$$\begin{aligned}\text{Material costs} = {} & 0.52\ \$/\text{lbs} \times 10.52\ \text{lbs} \\ & - 0.07\ \$/\text{lbs} \times 2.92\ \text{lbs} = 5.27\ \$ \end{aligned} \tag{23}$$

The raw material costs, the revenue earned from selling scrap, and the total material costs for each process are summarized in Table 21. A comparison of the values for the processes involved in the main routings indicates that process D is the most expensive in terms of material. For the production of the additional component via a subrouting, it can be observed that the material costs for process X are less than for process Y.

Table 21. Material costs of processes

Process	**Raw material cost [$]**	**Scrap revenue [$]**	**Material cost [$]**
A	5.47	0.2	5.27
B	-	-	-
C	5.47	0.2	5.27
D	5.8	0.21	5.59
E	-	-	-
F	-	-	-
G	-	-	-
X	0.18	0.06	1.12
Y	1.41	0.12	1.29
Z	-	-	-

- **Lubrication oil costs**

In the investigated plant, two different types of oil are used for the lubrication of machines. The purchasing prices per gal for these two types are 12 \$/gal and 14 \$/gal . Equation 11 is applied to calculate the lubrication costs of each process for processing one part. An example for process B can be seen in Equation 24.

$$\text{Lubrication oil costs} = 12\ \$/\text{gal} \times 0.00017\ \text{gal} = 0.002\ \$ \tag{24}$$

The lubrication costs of all processes are displayed in Table 22. It stands out that the costs values of all processes are marginal in comparison to other cost categories.

Table 22. Lubrication oil costs of processes

Process	**Lubrication oil costs [$]**
A	0
B	0.002
C	0.005
D	0.001
E	0.0009
F	0
G	0
X	0.0002
Y	0.002
Z	0.0014

- **Water costs**

  As indicated before, only process A uses deionized water for cooling. The deionized water is purchased at a price of 5.80 $/gal. According to Equation 12, this cost factor is multiplied with the water consumed for processing one part. The calculations for process A can be seen in Equation 25. With 0.02 $ the costs for water of process A are significantly higher than the costs for lubrication oil of the other processes. This shows that deionized water is a cost intensive-medium.

$$\text{Water costs} = 5.80\ \$/\text{gal} \times 0.0034\ \text{gal} = 0.02\ \$ \tag{25}$$

- **Consumables costs**

  The costs for various consumables that are needed for the processes are summed up to a cost factor for consumables per year for each process. Equation 13 is applied to calculate the consumables costs for processing one part. Sample computations are shown for process A in Equation 26.

$$\text{Consumables costs} = \frac{4120\ \$/\text{yr}}{2000\ \text{h}/\text{yr}} \times 75\ \text{s} \times \frac{1\ \text{h}}{3600\ \text{s}} = 0.043\ \$ \tag{26}$$

Table 23 displays the cost for consumables in manufacturing a part for all processes. For processes E, G, and Z, no consumables costs are identified.

Table 23. Consumables costs of processes

Process	**Consumables costs [$]**
A	0.043
B	0.027
C	0.07
D	0.099
E	0
F	0.003
G	0
X	0.0014
Y	0.026
Z	0

Finally, all cost categories are summed up and the total costs of each process are calculated according to Equation 14. Table 24 displays the total costs of the processes as the results of the cost analysis of the case study data. It stands out that the processes A, C, and D cause the most costs. The total costs of process D even exceed the costs of the other two processes by about 15 %. In comparison to these values, the costs of the processes B, E, and Z are relatively low.

Table 24. Total costs of processes

Process	**Total costs [$]**
A	6.86
B	0.72
C	6.88
D	7.98
E	0.66
F	1.30
G	1.03
X	2.04
Y	1.88
Z	0.71

Figure 37 illustrates the contributions of the different cost categories to the total costs of each process. It shows that the labor costs and material costs account for the major shares of the total costs. For some processes, the energy costs have a significant impact on the total process costs. The influence of the costs for water and lubrication can be identified as marginal.

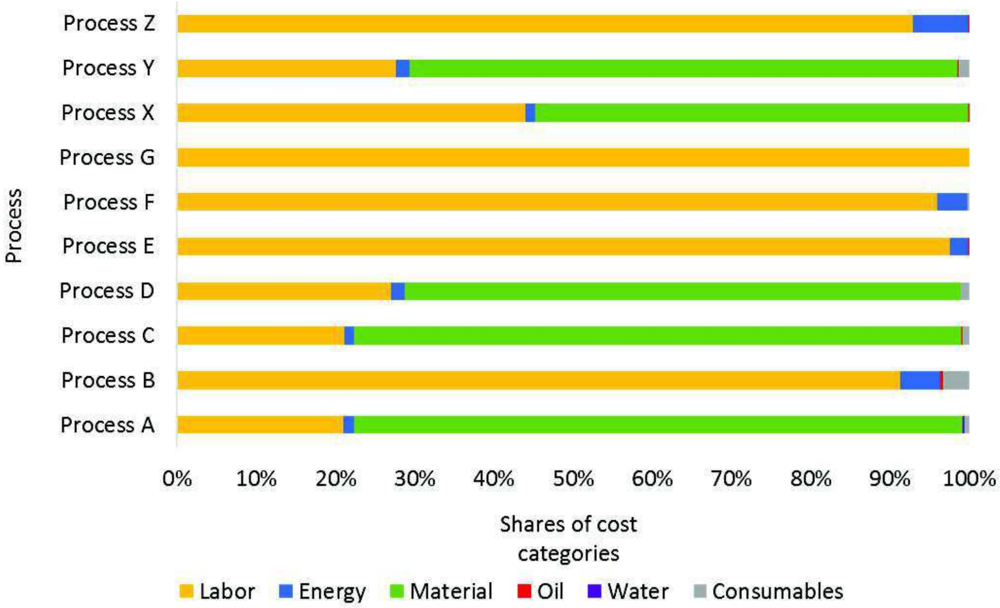

Figure 37. Share of the different cost categories

The results of the cost evaluation of the case study data provide an overview of all significant costs and thus support the company in examining their processes in terms of economic performance. Furthermore, the total costs of the investigated processes are used to compare the different potential process routings with one another in Chapter 5.

4.4. Environmental Impact Assessment

Within the environmental analysis of the process data, the environmental impact of the investigated processes is evaluated using the method of life cycle assessment. As explained in Section 3.3.2, only the raw material phase and the manufacturing phase of the part's life cycle are considered for the analysis. The functional unit of the study on which all calculations are based is one unit of the investigated part. The input and output data entered into the software Umberto NXT LCA is taken from the measurement results of the case study. Table 25 displays the relevant flows and the corresponding values for every process. Raw materials, energy, lubrication oil, and water are input flows while scrap is considered as an output of a process.

Table 25. Process data for the life cycle assessment

Process	Mat. [lbs]	Energy [Wh]	Oil [gal]	Water [gal]	Scrap [lbs]
A	10.52	540.08	0	0.02	2.92
B	0	214.81	0.00017	0	0
C	10.52	513.98	0.00044	0	2.92
D	10.55	772.99	0.000096	0	2.95
E	0	91.69	0.000072	0	0
F	0	293.61	0	0	0
G	0	0	0	0	0
X	1.9	141.54	0.000017	0	0.9
Y	1.72	188.36	0.000165	0	1.72
Z	0	290.61	0.000105	0	0

In order to account for the supply processes of the different input flows, generic data sets are used. Those data sets provide predefined processes which include all upstream activities in supplying the inputs. An overview of the data sets used for this study alongside an icon for each predefined process can be seen in Table 26. The data sets are all retrieved from the database ecoinvent v3.3.

Table 26. Generic data sets used for the LCA

Flow	Data set	Icon
Electricity	Market for electricity, high voltage [WECC, US only]	🟨
Lubrication oil	Market for lubricating oil [GLO]	🟩
Deionised Water	Market for water, deionised, from tap water, at user [RoW]	🟧
Metal sheets	Market for steel, chromium steel 18/8 [GLO]	🟪

The gathered data and the generic data sets are entered into Umberto NXT LCA by creating a petri net for each process. Examples for these petri nets can be seen in Figure 38 which displays the models for the processes A and B. The model for process A is divided into two phases and has two output flows, as the process uses raw materials and produces a unit of WIP and scrap.

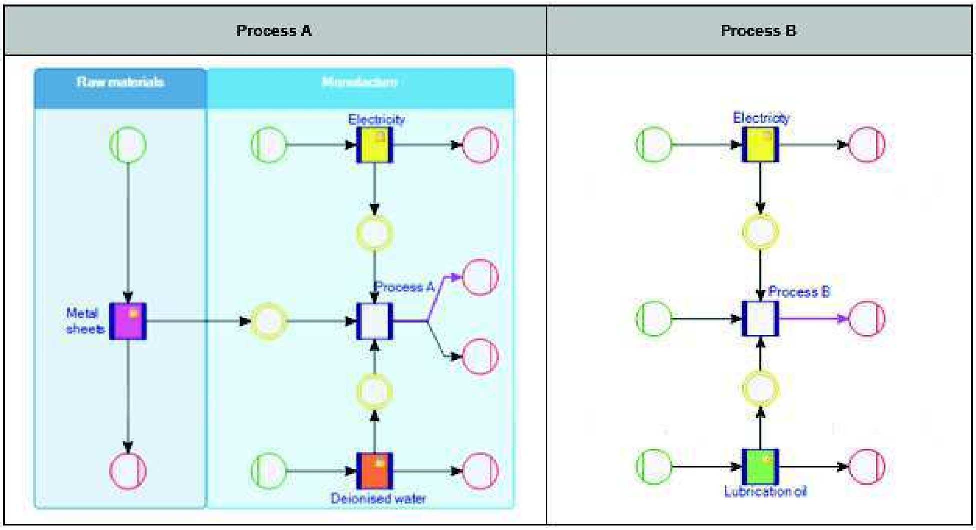

Figure 38. Exemplary models for processes A and B

After all process models have been created and all data has been entered, the environmental impact of the processes is assessed using the ReCiPe midpoint method within Umberto NXT LCA. The results of the impact assessment show significant values for two of the impact categories: the global warming potential and the acidification potential. Therefore, only these two categories are considered for the analysis of the case study data. The results for the two categories can be seen in Table 27. The impacts during the raw material and the manufacture phase are identified.

Table 27. GWP and AP of processes divided by the life cycle phases

Process	**GWP** $[CO_{2_{eq}}]$		**AP** $[SO_{2_{eq}}]$	
	Raw Mat.	**Manufacture**	**Raw Mat.**	**Manufacture**
A	22.43	6.35	0.12	0.0307
B	0	0.102	0	0.00031
C	22.43	6.34	0.12	0.0308
D	22.49	6.52	0.12	0.031
E	0	0.043	0	0.0001
F	0	0.14	0	0.0004
G	0	0	0	0
X	4.05	1.95	0.02	0.01
Y	5.79	3.68	0.031	0.019
Z	0	0.141	0	0.0004

It stands out that the values during the raw material phase are significantly higher than those during the manufacture phase for the processes which use raw materials. As Figure 39 illustrates, the production of raw materials accounts for 60%-80% of the global warming potential of those processes. For the acidification potential, the shares of the raw material phase are similar.

However, possible changes of the raw materials used or improvements in the processes of the suppliers are not considered in this study. The focus is on routing decisions within the manufacturing plant and therefore on the manufacture phase of the part's life cycle. Thus, the environmental impacts that result from the production of raw materials can be neglected. Table 28 displays the environmental impacts again just for the manufacturing phase.

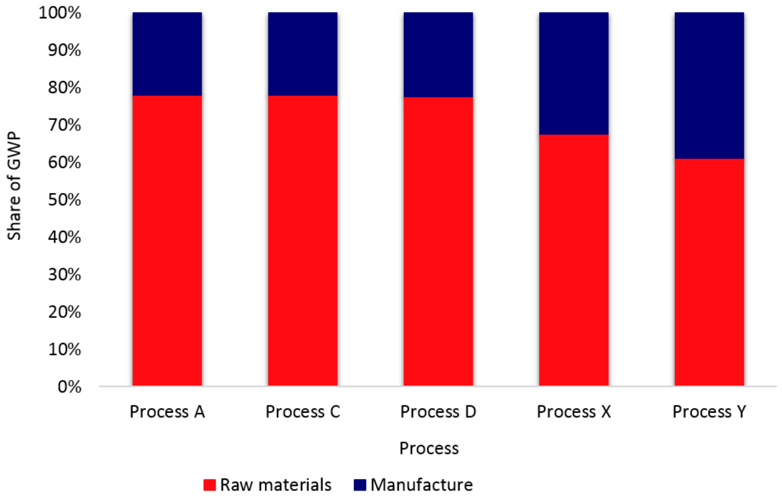

Figure 39. GWP share of the life cycle phases

Table 28. GWP and AP for the manufacture phase

Process	**GWP** $[CO_{2_{eq}}]$	**AP** $[SO_{2_{eq}}]$
A	6.35	0.0307
B	0.102	0.00031
C	6.34	0.0308
D	6.52	0.031
E	0.043	0.0001
F	0.14	0.0004
G	0	0
X	1.95	0.01
Y	3.68	0.019
Z	0.141	0.0004

The processes A, C, D, X, and Y still have higher impact values than the other processes. The reason for this is that these processes not only consume raw materials, but also produce scrap. In Figure 40, the contributions of the different input and output flows of processes to the environmental impacts are illustrated. It shows that the remaining scrap after the operation accounts for the major shares of the GWP and the AP of the processes. This means that scrap is of special significance for the environmental impact of the processes investigated in this study. In comparison to scrap, the impacts of oil and water are only marginal as just low volumes of these inputs are used by the processes.

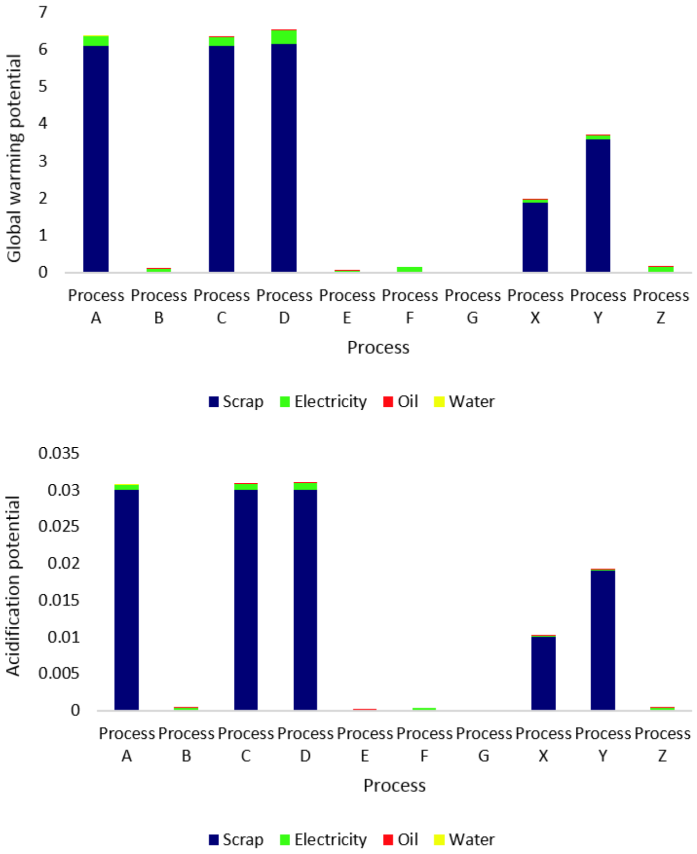

Figure 40. GWP and AP divided by flows

The results of the environmental impact assessment give information about the ecological performance of the processes in the case study. This knowledge supports the investigated company in reflecting on their impact on the environment. Furthermore, the detailed analysis of the contributions of the various input and output flows to the impact categories points out improvement potentials to reduce the environmental impact of the processes. In the following chapter, the data gained from this analysis is used as a performance indicator to evaluate the possible process routings in terms of their environmental impact.

5. Sustainable Routing

In this chapter, the multiple potential routings to manufacture the investigated part in the case study are compared with one another. The sustainability of routings is examined in detail by taking the economic and environmental performance of routings into account. It is shown how preferences for certain performance indicators can be set if the results of the comparisons are contradictory. Benefits from sustainable routing decisions in the case study are pointed out by analyzing possible improvements of the current situation in the company. Furthermore, a conceptual method to approach sustainable routing in manufacturing enterprises is derived from the specific example in the case study.

5.1. Comparison of Routings

For the comparison of routings, the economic and environmental performance metrics derived from the process data are used. Before evaluating the overall sustainability of the different options, an economic comparison and an environmental comparison of the routings are presented separately. The comparisons can be seen as follows:

- **Economic Comparison**

  In order to assess the economic performance of routings, the total costs of each routing are calculated as the sum of the costs of all processes involved in the respective routing. Table 29 displays the total costs of all possible routings in manufacturing one part. Routing 2 is the cheapest option with total costs of \$11.91 per part. There is a margin of \$1.65 per part between the cheapest and the most expensive potential routing.

Table 29. Total costs of routings

Routing	Total costs [$]
1	12.61
2	11.91
3	13.01
4	13.16
5	12.46
6	13.56

In Figure 41, the total costs of each routing are broken down into the costs of the processes that each routing contains. The first process in each routing accounts for the major share of the overall costs. Routing 2 and routing 5, the two cheapest options, both include process C as the starting process. As shown in the figure, the costs for process C are less than for the processes A+B and D which are other potential starting processes of the routings. Therefore, it can be concluded that process C is the best choice in terms of costs to begin the manufacturing of the investigated part.

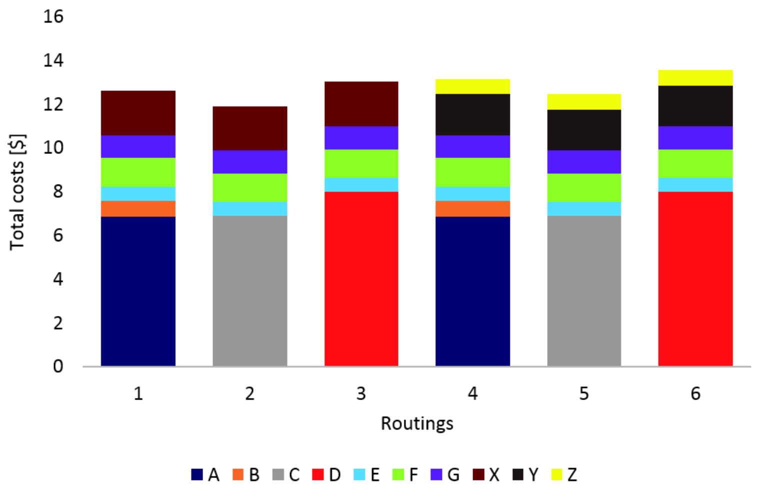

Figure 41. Contributions of processes to the total routing costs

As pointed out in Section 4.1, there are two possible sub-routings to manufacture additional components that are needed for the part. It stands out that the total costs of routings 1 - 3 are exactly \$0.55 less than those of the routings 4 - 6. This is the cost difference between the two sub-routings which costs are presented in Table 30. It is more cost-effective to use process X for the manufacture of the components than the combination of processes Y and Z.

Table 30. Total costs of sub-routings

Sub-routing	**Total costs [\$]**
X	2.04
Y+Z	2.59

- **Environmental Comparison**

  For the environmental comparison of routings, the environmental impact of each routing is retrieved from the software Umberto NXT LCA. Therefore, each routing is implemented as a petri net into the software by using the models created for the environmental analysis of the process data. The model created for routing 1 is displayed in Figure 42.

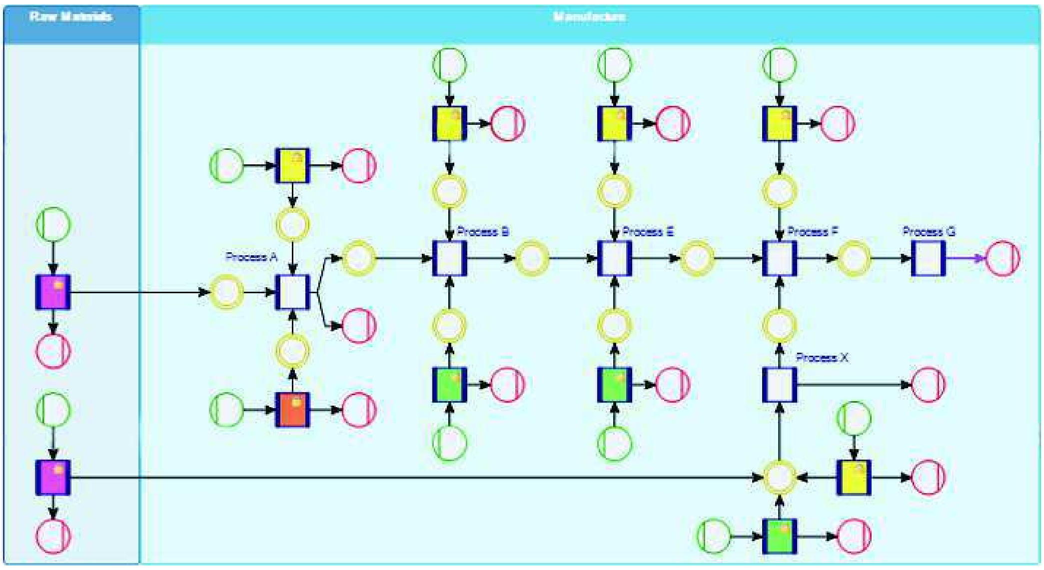

Figure 42. Model for routing 1 within Umberto NXT LCA

As explained in Section 4.4, the environmental impact during the raw materials phase is neglected and only the results regarding the manufacture phase of the part are considered. The global warming potentials and the acidification potentials of the process routings are shown in Table 31. Routing 2 has the lowest global warming potential per part with 8.47 $CO_{2_{eq}}$. These are 2.05 $CO_{2_{eq}}$ less per part compared to the option with the highest environmental impact which is routing 6. Choosing routing 2 also results in the least acidification potential. The routings are ranked equivalently by the two impact categories. However, the values for the acidification potential of the routings do not differ by that much from one another.

Table 31. Environmental impacts of routings

Routing	**GWP** $[CO_{2_{eq}}]$	**AP** $[SO_{2_{eq}}]$
1	8.58	0.0417
2	8.47	0.0415
3	8.65	0.0417
4	10.46	0.051
5	10.35	0.051
6	10.52	0.051

The contributions of the various processes to the environmental impact categories are illustrated in Figure 43. As for the total costs, processes A, C, and D account also for the major shares of the global warming potentials and the acidification potentials of the routings. However, there is not much of a difference between the values of these processes. A significant discrepancy can be seen between the impact values of process X and Y. For this reason, the global warming potential and the acidification potential of the routings 1 - 3 are lower than those of the routings 4 - 6. A further look at the environmental impacts of the two sub-routings is taken in Table 32. Process X has more than 50% less impact on the environment than the combination of the processes Y and Z to produce the components.

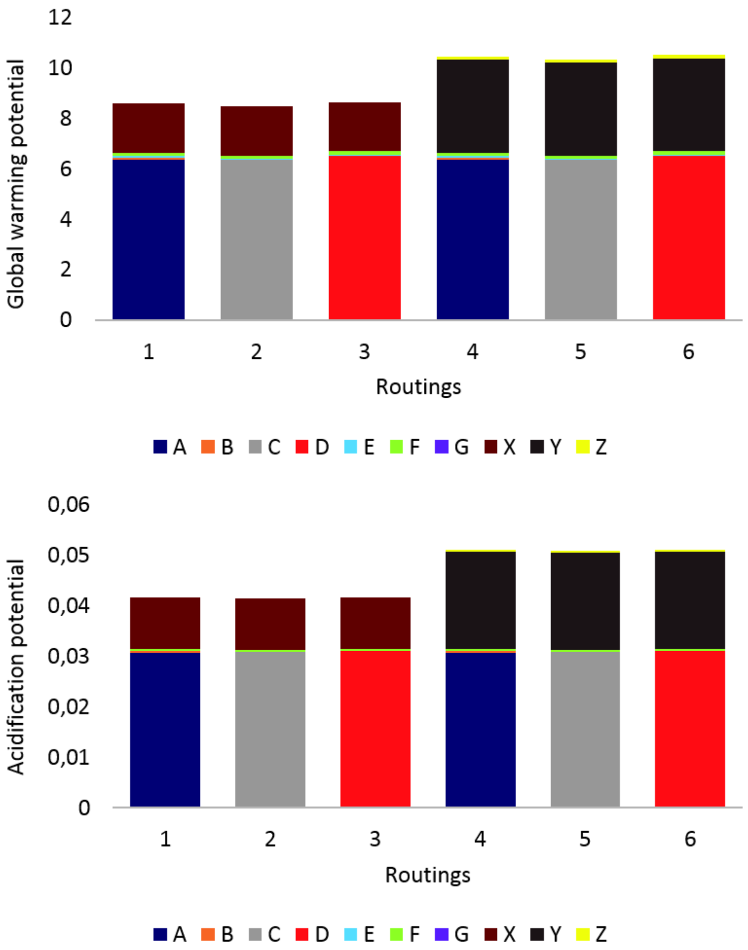

Figure 43. Contributions of processes to the environmental impacts of routings

Table 32. Environmental impacts of sub-routings

Sub-routing	**GWP** $[CO_{2_{eq}}]$	**AP** $[SO_{2_{eq}}]$
X	1.95	0.0102
Y+Z	3.82	0.0196

In order to make sustainable routing decisions, both dimensions need to be considered at the same time. In Figure 44, the total costs of the routings are plotted along with their global warming potentials. As shown in Table 31, the acidification potential leads to the same ranking of routings as the global warming potential. Therefore, just the global warming potentital is considered as an environmental impact category for further comparisons.

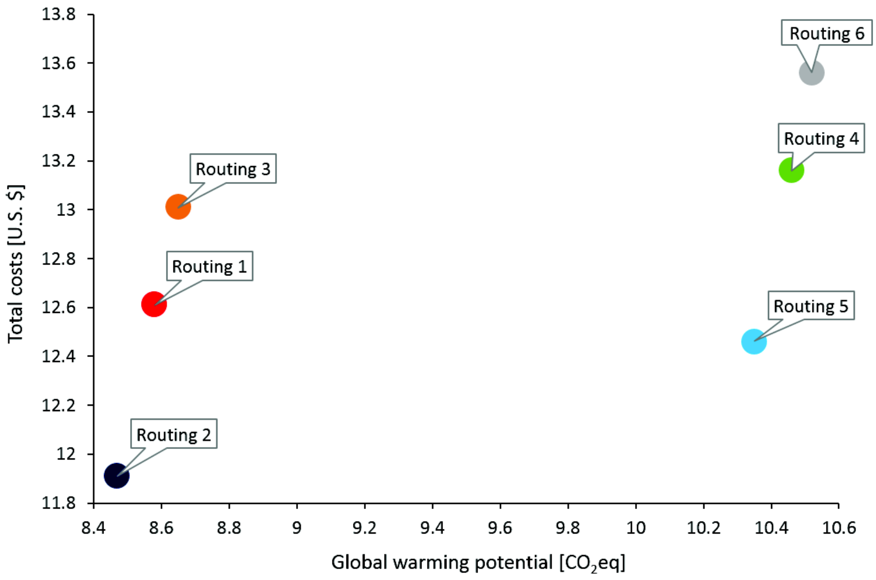

Figure 44. Total costs plotted against the GWP of routings

The point representing routing 2 is located in the bottom left hand corner of the diagram, as routing 2 has the least total costs and causes the least impact on the environment. Thus, the choice of routing 2 to manufacture the investigated part can be identified as the best case scenario in terms of both the economic and environmental performance. When it comes to the identification of the second best option however, the results are not that clear. While routing 5 results in less costs than routings 1 and 3, its global warming potential is much higher than those of the other routings. In order to make a decision in a case like this and favor one routing over another, preferences on the performance indicators must be set.

In this study, examples for different preferences are given to show how the two performance indicators can be weighted in order to rank the routings in the investigated company. To compare weighted performance indicators with one another, the values for the total costs and global warming potential are normalized using Equation 27.

$$\text{Normalized value} = \frac{\text{Value} - \text{Minimum}}{\text{Maximum} - \text{Minimum}} \tag{27}$$

The normalization of the values assigns a value of 0 to the routing with the lowest value for the respective performance indicator and a value 1 to the routing with the highest value. Figure 45 illustrates two examples for different weights of the performance indicators.

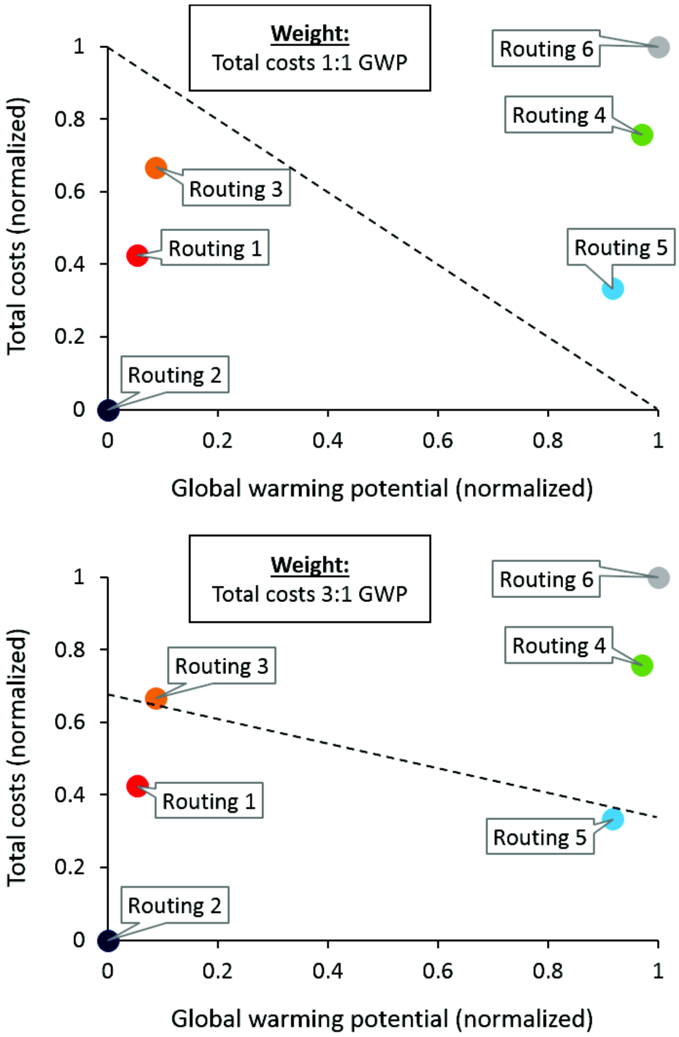

Figure 45. Examples for weights of performance indicators

Points which lay on the left hand side of the dotted line within the diagram dominate points which are to the right of it. For the first example which can be seen at the top of Figure 45, both performance indicators are weighted equally in a ratio of 1:1. In this case, routings 1 and 3 are preferred over routing 5 although their total costs are higher. For the second example, it is assumed that most companies regard costs as more important than the environmental impact. Therefore, the total costs are favored by a ratio of 3:1. This change of preferences puts routing 5 in favor of routing 3 as the total costs of routing 5 are significantly lower.

The examples show that the ranking of routings highly depends on the preferences set by the company if there are contradictory results for the considered performance indicators. However, in this case study routing 2 is clearly identified as the best option in terms of both performance indicators. Thus, the company is recommended to choose routing 2 to produce the investigated part. In order to evaluate the benefits for the company that result from this selection, the best case scenario is compared to the currently most common situation in the company. As indicated in Section 4.1, routing 3 is most frequently used to manufacture the part. Table 33 shows the values of the performance indicators for routings 2 and 3 and the potential savings per part that result from switching to routing 2.

Table 33. Potential savings by switching to best case scenario

Performance Indicator	**Best Case**	**Current Case**	**Savings (Absolute)**	**Savings (Relative)**
Costs [\$]	11.91	13.01	1.10	8.5%
GWP [$CO_{2_{eq}}$]	8.47	8.65	0.18	2.1%
AP [$SO_{2_{eq}}$]	0.0415	0.0417	0.0002	0.48%

The company in the case study can save \$1.10 per part by switching to routing 2, equaling a cost reduction of 8.5%. The change of the routing to manufacture the part is not only cost-effective, but also leads to a reduction of the environmental impact of the production. The global warming potential can be reduced by 2.1% and the acidification potential by 0.48%. In order to derive the potential annual savings from these values, the annual volume of the part must be identified. In the case study, just one specific size of the whole part family is considered. The selected size can be regarded as a medium size within the spectrum of the part family. Therefore, it is assumed that the investigated size of the part represents the whole part family. This means that the savings per part is considered to be approximately equivalent for all part sizes. The annual production volume of the whole part family is provided by the company's management and adds up to 11,642 units per year. The potential annual savings resulting from switching to a more sustainable routing can be seen in Table 34. An annual cost reduction of $12,860.20 can be achieved. The global warming potential can be cut down by 2,095.56 $CO_{2_{eq}}$ and the acidification potential can be shortened by 2.33 $SO_{2_{eq}}$.

Table 34. Possible annual savings

Performance Indicator	**Annual savings**
Costs [$]	12,806.20
GWP [$CO_{2_{eq}}$]	2,095.56
AP [$SO_{2_{eq}}$]	2.33

In order to switch to routing 2 to produce the part and to benefit from the potential savings, the company in the case study has to examine the requirements for the change of routings. In this specific case, the main issue is the capacities of machines. To manufacture the total annual volume of parts via routing 2, a rescheduling of machines would be necessary. However, it must be ensured that the rescheduling does not increase the costs and environmental impacts of the production of other products from the company's portfolio. Another option is to increase capacities by investing in new production machines. The machine used for process D in routing 3 is relatively old and a replacement of this machine is already under consideration. The potential savings through a change of routings gives the investigated company additional incentives to think about new investments.

5.2. Development of a New Method

The case study has proven that sustainable routing decisions can lead to economic and environmental benefits for manufacturing companies. However, the case study just shows a customized approach for a specific example. For other cases, other process metrics and steps in the analysis of the data may be relevant. Based on the approach applied in the case study, a general method for sustainable routing in manufacturing companies is created. This method is designed conceptually and includes a step-by-step approach on how a company can implement sustainable routing in their production system. Figure 46 provides a schematic illustration of the method and the steps required for its utilization.

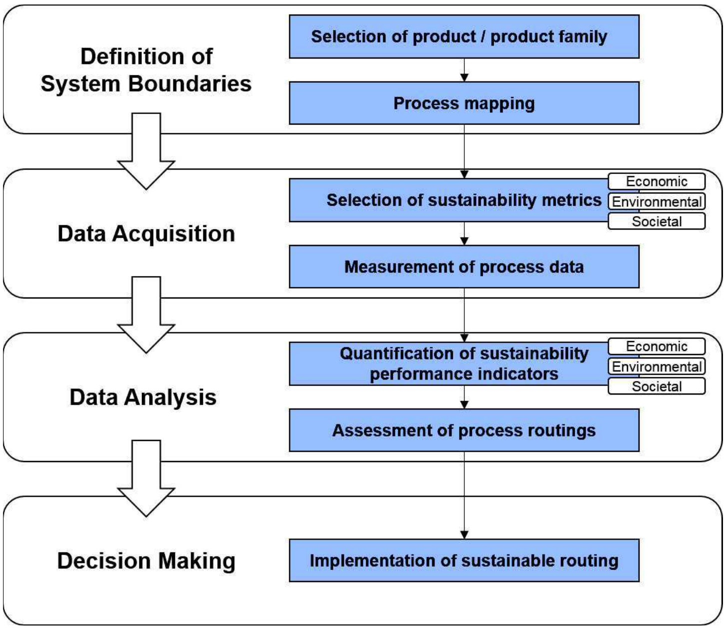

Figure 46. A method for sustainable routing

The new method for a sustainable routing in manufacturing is designed similar to other improvement methods in manufacturing and can be broken down into four elementary steps. Following, it is explained how the steps are conducted and how they can be configured for various applications:

1. **Definition of system boundaries**

   First, the system boundaries for the application of the method are defined to clarify under which scope conditions sustainable routing decisions should be made. This includes setting goals for the study and identifying the product or product family to be investigated. The decision of whether a whole product family or just a component of a product should be examined depends on the individual manufacturing system and the availability of multiple routings within it. In this case, it is also important to determine which phases and processes of the products manufacture should be included in the analysis. All potential routings for the respective product or product family including the involved processes are registered. To support this step, a process map is created to visualize the different options. A process map increases the awareness of the various routings among the employees and thus helps to establish a system's perspective within the organization.

2. **Data acquisition**

   Process data is gathered to characterize the processes included in the different routings. Therefore, appropriate metrics to be measured are selected that display the sustainability of processes. According to the triple bottom line, economic, environmental, and societal metrics must be considered. In general, economic metrics include traditional metrics that are measured in a time study. For the environmental dimension, all energy and material flows within the system that are important for the manufacture of the investigated product should be examined. However, it must be kept in mind that some of these flows have also an impact on the economic performance of processes such as the costs resulting from energy consumption. Metrics for the social dimension could display the work environment, the health and safety of employees, or their fulfillment in their jobs. The significance of possible metrics varies across companies and industries, so metrics should be chosen depending on the individual case. All selected metrics are quantified using appropriate measurement techniques. In order to compare various processes and routings with one another, it must be ensured that all measurements refer to the same functional unit. For instance, the functional unit can be a certain production volume or time period. The results of the data acquisition are visualized in a sustainable value stream map. The sustainable value stream map provides an overview of the whole system and gives an insight into the relevant process data.

3. **Data analysis**

   Within the analysis of the process data, performance indicators for all three dimensions are derived from the data. Available techniques and tools for the different dimensions may be used to support this step. For the economic dimensions, a possible way to compare processes with one another is assessing their total costs. The method of life cycle assessment can be used to identify the environmental impacts of the processes. If a life cycle assessment is conducted, adequate impact categories for the analysis must be selected. The potential process routings to produce the selected product or product family are evaluated and compared according to these performance indicators. If the performance metrics lead to contradictory results for the three dimensions of sustainability, trade offs must be found. For this purpose, preferences for the performance indicators can be set to favor one dimension over another.

These preferences should be chosen according to the individual case and the objectives of the respective company.

4. **Decison making**

   The assessment of the routings results in a ranking of the different options so that the best and worst case scenario can be identified. Furthermore, it enables an evaluation of the status quo in the investigated production system. This means that potential for improvements of the current situation through sustainable routing could be exposed. In this case, a decision must be made if the current favored routing in the investigated company should be replaced by a more sustainable routing. Therefore, the benefits of the implementation of the results must be examined for all three sustainability dimensions. Furthermore, the requirements for changes and their effects on other aspects of the production system need to be considered as well.

The method does not contain specific details on how to approach sustainable routing in manufacturing companies as its configuration highly depends on the individual case. However, it presents all the necessary steps and aspects that must be considered in order to make sustainable routing decisions. Thus, managements in manufacturing companies can use the method as guidance and adapt it to their individual needs.

6. Conclusion

In the conclusion, the objective, the procedure and the results of this study are summarized. The achievements of the work are acknowledged and critically discussed. This includes a review of the assumptions made and the limiting factors in this paper. Furthermore, a prospect on possible future research in the investigated field of study is given.

6.1. Summary

In recent years, market, environmental, and societal motivation factors have made sustainable manufacturing an important field in manufacturing research. In this context, the sustainability of a manufacturing system must also be considered when multiple potential process routings exist to manufacture a product. Therefore, the objective of this study is to develop a method that supports manufacturing companies to make sustainable routing decisions. In order to create a practical approach, a generalizable method is proposed.

To get an overview of the research field and to point out the significance of the study, a broad review of the existing literature is presented. In the literature review, the research topic of sustainable manufacturing is identified as an important aspect of a sustainable development. An investigation of the state of the literature in flexible routing underlines the potential of including sustainability in routing decisions in manufacturing companies. Examples of current approaches for sustainable manufacturing are given and differentiated by the level of an organization where they are applied. Sustainable value stream mapping and life cycle assessment are explained to show possible evaluation techniques for the sustainability of manufacturing systems. Furthermore, studies regarding the role of electrical energy, compressed air, lubrication oils, and material waste for manufacturing processes are presented. Various works in literature show that limited resources and a lack of applicability of available methods are the main obstacles for companies in becoming more sustainable. Based on all the reviewed literature, it is stated that there is a need for a new method for sustainable routing. When it comes to its design, ensuring the viability of the method is crucial.

Within the conducted case study, various possible routings are investigated to manufacture a product from a company's portfolio. All processes involved in these routings are identified and mapped to visualize the different options. Appropriate metrics to display the economic, environmental, and societal performances of those processes are selected. For each metric, the required process data is gathered and the procedure of data acquisition is described. Equations to process the data for the investigated product are given and the necessary computations are shown with an example for each metric. All process data is illustrated in a sustainable value stream map to provide an overview of the measurement results. In order to use the process data for decision making, performance indicators are derived which represent the economic and environmental performance of the processes. For the economic analysis of the data, a cost evaluation is carried out. The costs for each metric are derived and summed up to calculate the total costs of a process. To determine the environmental impact of processes, a life cycle assessment is employed. Within this analyis, the global warming potential and the acidification potential of the processes are quantified.

The potential routings to manufacture the product in the case study are compared with one another using the identified performance indicators. An economic, an environmental, and an overall comparison of routings are provided. Within the assessment of routings, a method is presented on how to assign preferences to certain performance indicators if the results of the economic and environmental comparisons are contradictory. With an example, it is shown how the case study company can make routing decisions in a case like this. Furthermore, the best case scenario and the current situation in the company are compared with one another. It is concluded that savings in both costs and environmental impacts can be achieved by making sustainable routing decisions.

Finally, a general method for sustainable manufacturing is created based on the conducted study. The approach is conceptually designed to be applicable for various applications in manufacturing industries. It is comprised of four elementary steps: definition of system boundaries, data acquisition, data analysis, and decision making. The aspects of each step are specified within the framework and can be scaled for individual purposes.

6.2. Discussion

The method developed in this study can be used as a guidance by manufacturing companies to achieve a more sustainable way of manufacturing by approaching routing problems in their production system. It provides an overview of the most important aspects to consider when sustainable routing decisions should be made. This supports the initialization and the management of the improvement process. The practicability of the method has been proven in the conducted case study. However, individual manufacturing systems differ from one another which means that further advantages or disadvantages of the method could exist for other cases of application.

In the case study, it is shown how a manufacturing company can achieve savings in costs and environmental impacts by producing a part after applying sustainable routing decisions. It must be noted that the annual savings were determined for one type of the part family and then assumed equally for the whole part family. A more detailed analysis to identify the exact potential savings for the company is necessary in this case. Furthermore, the requirements of switching from one process routing to another must be investigated further. In particular, this concerns the utilization of machine capacities which must be considered in routing decisions. Additionally, a look for synergies between routing decisions and other aspects in the investigated production system may justify additional investments.

The case study expounds how various metrics for the sustainability of processes can be considered in the analysis. Special mention must be made of the approach applied to quantify the energy consumption due to compressed air usage of processes in manufacturing one unit of a product. It is explained how the energy consumed to provide compressed air within a factory can be assigned to single processes. This leads to transparency regarding the usage of compressed air in a manufacturing system. However, the number of investigated metrics in the case study is limited and the circumstances in other practical cases may regard other metrics as important. For instance, the quality of products and the productivity of processes could also be interesting in terms of the economic performance. Furthermore, the availability of machines could be a highly relevant metric, as not working machines result in high opportunity costs for a company. Additional environmental impacts could result from the usage of cooling lubricants and heat for production processes. The social dimension of sustainability was only briefly addressed in the case study. To assess the social impacts of processes, further societal metrics must be taken into account. The ergonomics of workplaces and other factors which affect the health and safety of employees could be investigated.

One of the most difficult problems with regards to sustainable manufacturing is to find trade-offs between the three dimensions. In the case study, a method is presented for setting preferences on performance indicators in order to find trade-offs. However, just two of the three dimensions are considered in the presented example. Furthermore, it is unclear based on which reasons a manufacturing company decides on certain preferences. In the example, the preference values are just selected arbitrarily and not based on any targets or numbers in the investigated company.

6.3. Future research

In future research, the method must be applied in further case studies across manufacturing industries to prove its general applicability. A more detailed look should be taken at the requirements and obstacles to implement sustainable routing in manufacturing companies. In this context, the detailed insight into the performance of processes gained during the application of the method could be used to identify synergies between sustainable routing and other improvement methods for manufacturing systems. Furthermore, other metrics and how they can be quantified to display the sustainability of processes should be considered in further studies. In research, not a lot of attention has been given to the societal impact of manufacturing processes which opens up potential for further studies in this field. For a complete analysis of the sustainability of a manufacturing system, all three dimensions must be taken into account for decision making. This requires a further investigation on how trade-offs between the three dimensions can be found in manufacturing enterprises. For this purpose, a performance indicator could be developed that represents all dimensions at once. According to the results of future research, the developed method for sustainable routing may be revised to improve its suitability for industrial manufacturers.

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