Lappeenranta-Lahti University of Technology LUT
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APPLYING MATERIAL FLOW COST ACCOUNTING TO OPTIMIZE THE MATERIAL EFFICIENCY OF A COMPANY PRODUCING METAL PRODUCTS

Master’s thesis 2019

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TIIVISTELMÄ

Tekijä:	Tiina Kämpjärvi
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Valmistaville yrityksille on tärkeää materiaalitehokkuuden optimoiminen materiaalihukkien syntymisen vähentämiseksi. Materiaalihukkia pidetään prosessien arvottomina tuotoksina, koska ne heijastavat tehottomuutta. Tämä tutkimus keskittyy mittaamaan kohdeyrityksen nestaus prosessissa käytettyjen eri metallilevykokojen materiaalitehokkuutta. Tutkimuksen tavoitteena on verrata eri metallilevykokojen tuottamia materiaalihukan määriä. Vertailun perusteella voidaan optimoida levykoot, vähentää materiaalihukan määrää ja saavuttaa kustannussäästöjä.

Tämä opinnäytetyö on tapaustutkimus, jossa sovelletaan kvantitatiivista tutkimusmenetelmää. Tutkimuksen empiirisen osuuden tiedonkeruu perustuu sekundäärilähteisiin. Tutkimusdata on kerätty kohdeyrityksen nestaustilastoista koskien eri levykokoja. Kerättyä nestausdataa käytetään empiirissä osuudessa materiaalivirtojen kustannuslaskennassa, jotta voidaan laskea eri levykokojen tuottama materiaalihukka. Tulokset osoittavat, että materiaalihukan määrään voidaan vaikuttaa eri levykoilla. Näin ollen vertailujen tulokset osoittavat kohdeyritykselle optimaaliset levykoot, jotka tuottavat sekä materiaalisäästöjä ja kustannussäästöjä.

ABSTRACT

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It is important for manufacturing companies to optimize their material efficiency in order to reduce the generation of waste in manufacturing. Waste is considered as a non-valuable output from a process because it reflects inefficiency. This thesis is focused on measuring the material efficiency of the metal sheets and plate sizes used in the nesting process of the case company. The objective is to compare the scrap generation between different metal plate sizes in order to examine improvement possibilities in terms of plate optimization, reduced amount of waste and cost savings.

This thesis is a case study that involves a quantitative research method. The data collection of this study is solely based on secondary data collection. The data is collected from the case company's nesting statistics regarding different metal sheet and plate sizes selected for this research. In the empirical part, the collected data is used in the material flow cost accounting analysis in order to calculate the scrap generated per each plate size in both physical and monetary units. The results show that the generation of scrap in nesting can be influenced by different sheet and plate sizes. Thus, the results of the comparisons provide the case company with optimal plate sizes that result in material savings and hence, savings in financial losses.

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In Varkaus, 1.11.2019

Tiina Kämpjärvi

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1 INTRODUCTION

The purpose of this study is to optimize the material efficiency of the metal sheets and plates used in the nesting process in order to achieve savings in financial losses, optimized plate sizes and reduction on scrap generation. This thesis aims at comparing the material efficiency of different metal plate sizes in both physical and monetary terms by using the material flow cost accounting method. This thesis is a single case study that involves a case company that manufactures metal products for the construction sector.

One of the biggest challenges faced by manufacturing companies are revenue leakages that results from production processes. Revenue leakages are associated with material inputs ending-up as waste. Due to revenue lost, waste is considered as expensive to manufacturing firms. (Tajelawi & Garbharran 2015, 3765) The negative effect of raw material ending up as material loss is that is loses its initial value (Schmidt 2010, 556). Doorasamy (2016, 263) states that waste is expensive for companies due to the material purchase value left as unused.

According to Wohlgemuth & Lütje (2018, 3) material flow cost accounting records the input and output flows of a process. Material flow cost accounting is a tool that aims to improve the use of resources by finding out the cost of waste (Yagi & Kokubu 2018, 764). MFCA aims to quantify material flows in both physical and monetary units in order to identify the real cost of waste (Wan, Ng, Ng & Tan 2015, 603). As a result, the cost of material losses should encourage companies to reduce their material losses from occurring (Kokubu & Tachikawa 2013, 354).

Material flow cost accounting is mainly important for manufacturing firms since cost related issues are crucial to them (Schmidt 2015, 1310). For most manufacturing companies, materials provide the main cost saving potential since materials often account for 50% of the production costs (Gould & Colwill 2015, 2). According to Tajelawi & Garbharran (2015, 3765) the effectiveness and financial performance of a manufacturing company are directly proportional to the cost factors of the company. Thus, it can be concluded that materials provide the greatest potential to increase efficiency (Schneider, Härtwig, Kaltschew, Langer & Prietzel 2015, 115). In order to gain savings on material and material costs, it is a matter of importance to concentrate on material efficiency (Schmidt, Hache, Herold & Götze 2013, 231). According to Fischer (2013, 102) companies can gain significant yearly savings by implementing simple and low-cost material efficiency measures. According to Schneider et al. (2015, 115) even a small reduction in material costs can contribute to improving the company's competitiveness and therefore, it is desirable to achieve a higher efficiency in production processes.

1.1 Research aims and questions

The case company of this thesis generates scrap in manufacturing. The problem with scrap is that it ties up monetary value that could be saved in order to avoid the generation of monetary losses. Thus, it is important to reduce the amount of scrap generated in order to contribute to the profitability of the case company. The purpose of this study is to improve the material efficiency of metal sheets and plates used in the nesting process. The aim is to compare the amount of scrap generated between different plate sizes used in the nesting process. The expected benefits of this thesis are reduced amount of scrap, optimized plate sizes and savings in financial losses. To achieve these, this thesis applies material flow cost accounting in order to calculate the physical quantities of the material loss generated per each sheet and plate size as well as the associated monetary value.

The main research question of this research is as follows:

How can the material efficiency of the nesting process be improved?

In order to give an answer to the main research question, a set of sub-questions are set. The sub-questions are as follows:

RQ1: How does waste reduction in manufacturing processes contribute to material efficiency?

RQ2: How do different plate sizes effect material efficiency in the nesting process?

RQ3: How can waste generation be measured in order to improve material efficiency?

RQ4: What is the difference in material efficiency measured in both physical and monetary terms between different metal plate size categories?

RQ6: How much should the width of 1500mm cost in order to achieve the same costs in the total amount of waste (€) generated in the width of 2000mm?

1.2 Key concepts

This section outlines the key concepts of this study. These are waste, scrap, nesting, material efficiency and material flow cost accounting. The definitions of these concepts are provided next.

According to Thürer, Tomašević & Stevenson (2017) **waste** is considered something valuable that loses its value such as material. Waste occurs for instance because too much of something valuable is consumed or because it is used in an ineffective way (Thürer et al. 2017, 245). Corvellec (2016, 7) refers to waste as a type of failure. Pacelli, Ostuzzi & Levi (2015, 80) state that waste is a non-value outcome of a manufacturing process. According to Kurdve, Shahbazi, Wendin, Bengtsson & Wiktorsson (2015, 306) waste is non-productive output in the form of any substance or object that is disposed of.

Pacelli et al. (2015 79) refer to **scrap** as a type of waste. According to Huda (2018, 1) scrap is part of production and the outcome of a production failure. According to

Vrat (2014, 227) scrap is an undesirable outcome of manufacturing processes. According to Shahbazi, Jönsson, Wiktorsson, Kurdve & Bjelkemyr (2018, 25) process scrap is hard to avoid.

Material efficiency is associated with the amount of material used in manufacturing a product. Material efficiency can be improved by using a smaller amount of material in the production of a product or alternatively it can be improved by generating a smaller amount of waste in the production of a product. (Shahbazi, Wiktorsson, Kurdve, Jönsson & Bjelkemyr 2016, 438)

Products made of sheet metal are typically manufactured by different machines such as a cutting machine. To support the planning and machining, different kinds of software tools are used on the machines. Nesting software system is a tool that is used in the production to minimize waste and improve efficiency in production. (Xie & Xu 2008, 25-26) **Nesting** is defined as a process of deciding which parts should be cut from a sheet (Maimon & Dayagi 1995, 121). The aim of nesting is to place as many ordered parts as possible on a sheet in a way that the amount of waste is reduced to minimum (Verlinden et al. 2007, 371). Thus, nesting is used to minimize material waste and gain significant savings (Smith 2004, 31).

Material flow cost accounting (MFCA) provides material efficiency and cost saving opportunities in terms of raw materials. (Rieckhof, Bergmann & Guenther 2015, 1263) Doorasamy (2016, 271) states that the main principle of MFCA is to make a difference between the cost of product and material loss. This is achieved by quantifying material flows in a process in both physical and monetary units (Kokobu & Kitada 2015, 1280).

1.3 Theoretical framework

Next the theoretical framework of this study is presented. The framework shows how the theory of this this research is structured and how it supports the research problem of this study. According to Kananen (2010, 21), a theoretical framework is a combination of theories that have already been written about the subject under study. They are used to support the study as well as the research findings (Kananen 2010, 21). The theory is collected from secondary sources such as books, scientific journals and websites. Databases used to collect data are LUT Finna, Scopus, Springer and Google Scholar.

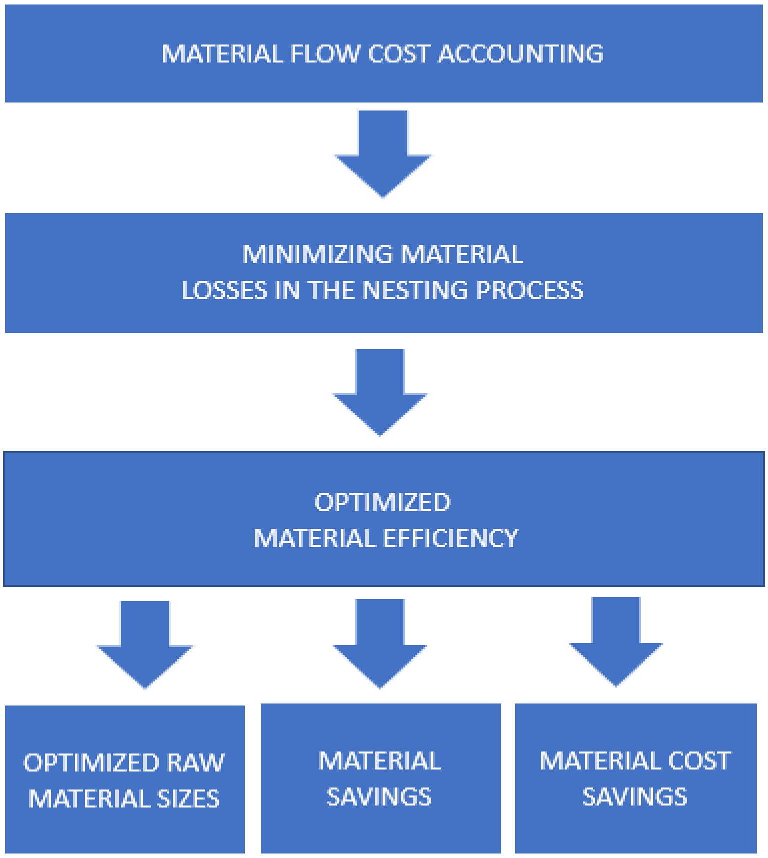

Figure 1. Theoretical framework

The theoretical framework of this study is shown in figure 1. The figure shows how MFCA is used to optimize material efficiency by minimizing material losses incurring in the nesting process. As a result, the benefit are optimized material sizes, material savings and material cost savings.

1.4 Organisation of the study

This section provides the structure of the thesis shown in figure 2. The chapter 1 aims to introduce the reader to the topic. In this chapter, the author presents the background, research aims and questions of this study.

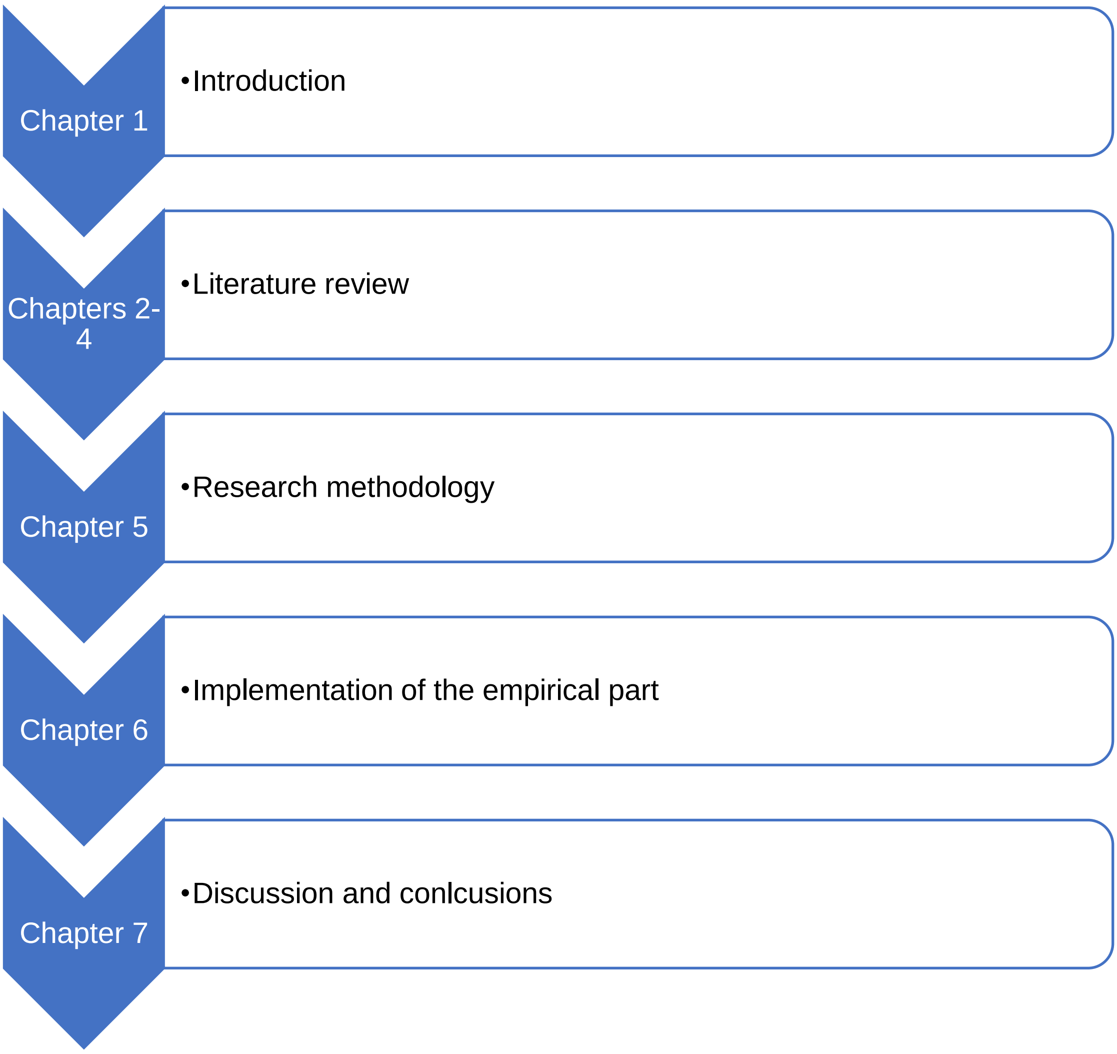

Figure 2. The structure of thesis.

The chapters 2-4 provide the literature review that cover relevant concepts such as nesting, material efficiency and MFCA. Chapter 5 presents the methodology including the case description, research methods, data collection and analysis. In Chapter 6 the empirical research of this study is carried out. In this part the author conducts MFCA analysis and provides the results. Chapter 7 concludes the thesis. In this chapter, the theoretical and empirical findings are discussed, the answers to the research questions are given, the reliability of the study is assessed, and the future research suggestions are given.

1.5 Research limitations

In order to make this thesis feasible, a few limitations are set for this study. According to Hirsjärvi, Remes & Sajavaara (2009, 81) it is typically important to make limitations to the selected topic. The first limitation to this study is that this study considers only the case company’s business operations in Finland. To be more specific, this study concentrates only on the case company’s composite beam production.

The second limitation is that this study examines only the material efficiency of metal plates which is one the most important raw material group of the case company. Thus, there is a possibility to realize significant cost savings for the case company by optimizing the material efficiency of the metal plates and sheets.

As a third limitations, this study considers only the material loss generated in terms of material efficiency. Thus, this study does not put attention to the output generated in terms of produced products per each metal plate. Nor does this study take into account throughput times or other capacity issues that are essential to consider when the aim is to maximize output generated in manufacturing.

The fourth limitation is that this study considers only scrap material that has been generated through the nesting process. Thus, this study does not take into account remnants that are leftover material that result from cutting a standard size stock material (Rajgopal, Wang, Schaefer & Prokopyev 2009, 437). Kos & Duhovik (2002, 2289) state that remnants can be re-used in the future if the size of the remnants part is large enough. Thus, it is possible to re-use remnants by cutting smaller pieces out of them (Rajgopal et al. 2009, 437). This limitation was made during the writing process of this thesis because it turned out that it would be difficult to obtain reliable calculations if remnants were included.

The fifth limitation of this study is that this study considers only the direct material cost of scrap which refers to the original purchase price of the material. Thus, other hidden costs of waste are left out from this study.

The last limitation is associated with the strategies in nesting to minimize the amount of scrap. In this study, the aim is to examine how different metal plate sizes contribute to the scrap generated. Thus, other methods to decrease scrap in nesting are excluded from this study.

2 MATERIAL EFFICIENCY IN MANUFACTURING

The second chapter is focused on material efficiency in manufacturing. This chapter begins by presenting the basic overview of material efficiency. The second part concentrates on introducing the financial impacts resulting from increased material efficiency. The third part of this chapter is concerned with presenting material efficiency strategies after which linear and circular production models are discussed. Lastly this chapter presents key performance indicators related to material efficiency.

2.1 The concept of material efficiency

The concept of efficiency relates to comparing the inputs put into a system with the outputs produced from the system. In the manufacturing context, material efficiency refers to physical resources used in a production process, which results in produced products that have an economic value. (Fischer 2013, 102) According to Shahbazi et al. (2018,18) material efficiency is associated with the quantity of materials needed to manufacture a product. Material efficiency aims to generate a smaller amount of waste per product or consuming a smaller amount of input material per product (Shahbazi et al. 2018, 18). Lifset & Eckelman (2013, 1-2) state that material efficiency means that less material is used in the production of a product or in the provision of a service. Söderholm & Tilton (2012, 75) define that material efficiency in the context of industrial production refers to using a certain amount of material to manufacture a certain product.

Skelton & Allwood (2013, 33) state that increased material efficiency has been driven by concerns over increased input scarcity, disposal of waste and emissions. According to Söderholm & Tilton (2012, 25) a greater material efficiency is motivated by the environmental benefits gained through using less material and the limited amount of natural resources. Lifset & Eckelman state (2013, 2-3) that material efficiency should reduce environmental impacts rather than just ensure mass-based material savings. Cordella, Alfieri, Sanfelix, Donatello, Kaps & Wolf (2019, 3) state that material efficiency refers to strategies that relate to the usage and management of resources during the product's whole life cycle with the purpose of minimizing the consumption of material, production of waste but also minimizing the associated environmental effects without having a negative impact on the functionalities.

The definition of material efficiency tends to vary depending on the discipline. The economic viewpoint defines material efficiency as producing the largest output possible with a given input or decreasing the amount of input to produce a certain amount of output. (Flachenecker et al. 2017, 2) Allwood, Ashby, Gutowski & Worrell (2013) state that, often, material efficiency refers to a physical measure. However, the economic perspective of efficiency takes into account money when measuring efficiency (Allwood et al. 2013, 7). Lilja (2015, 2030) states also that the economic view of efficiency takes into account monetary matters. Material efficiency can be improved in cases where material inputs are increased. In this case, greater material efficiency is achieved by paying a smaller price for the inputs or alternatively raising the price of the final product. However, in this situation, the environmental performance is not improved. (Lilja 2015, 2030)

2.2 Effects of increased material efficiency

According to Skelton & Allwood (2013, 34) material efficiency relates to the potential for achieving material cost savings. Doorasamy (2015, 56) concludes that a great potential lies in reducing material costs since material costs constitute the biggest costs in the manufacturing sector. Halme, Anttonen, Kuisma, Kontoniemi & Heino (2007, 126) state that companies should strive for material savings due to economic reasons. Figure 1 demonstrates how material savings can impact the financial performance of a company. Figure 1a shows a company having an annual sales of 100% from which 44,3% represent material costs, 3% are profits and 52,7% consists of other costs. Figure 1b) shows that when material costs are reduced by 2,4%, it directly improves the profit share from 3% to 5,4%. In comparison, figure 1c presents how much the company should increase its sales in order to achieve the same results in profits. Based on the calculations, sales should be increased significantly by 80%. Thus, it can be concluded that it requires less investments by a company to increase its profits by reducing material costs than increasing its sales. (Schneider et al. 2013, 117-118)

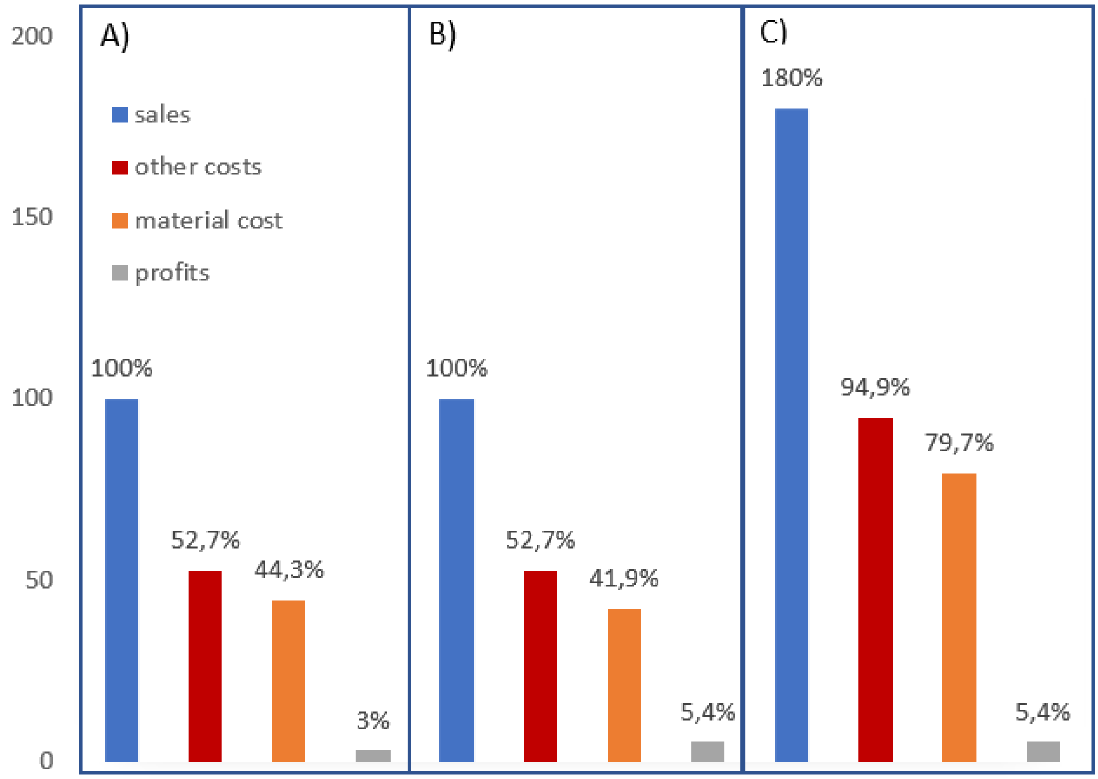

Figure 3. Impact of material savings on a company's profits (Adapted from Scheider et al. 2015, 120).

According to Smith (2014, 30) companies that achieve improved material utilization are typically more competitive in the market. According to Lilja (2009, 869) material efficiency improvement provides financial benefits such as savings in raw material purchases. According to Halme et al. (2007, 126) efficient use of materials usually leads to lower procurement costs. According to Flachenecker et al. (2017, 4-5) increased material efficiency leads to using relatively lesser amount of materials, which results in material savings. In addition, increased material efficiency leads to fewer purchases, which decreases uncertainty in terms of price volatility (Flachenecker et al. 2017, 6).

In Germany, it was examined, that the saving potential in direct material costs for small and medium-sized companies is on average 2,5% of the annual sales (Schmidt 2010, 554). According to Schneider et al. (2013, 116) the saving potential corresponds to an average saving potential of more than 200,000 €. Flachenecker et al. (2017, 7) state that the net benefit for firms in the EU area falls typically between 10%-17% of annual turnover, which translates into 27 500 – 424 000€ depending on the sector and size of the firm. The payback time for investing in material efficiency takes up less than six months (Flachenecker et al. 2017, 7).

2.3 Material efficiency strategies

Material efficiency can be enhanced, for instance, by using a smaller amount of materials in the production of a product or alternatively reducing the amount of waste that is created in the production of a product (Shahbazi et al. 2016, 438). According to Kurdve et al. (2015, 306) the waste hierarchy (illustrated in figure 4) shows, from business and environmental perspective, how material efficiency can be improved by managing waste. According to Cordella et al. (2019, 3), the waste hierarchy describes the material efficiency options. Singh and Sushil (2016, 786) state that the waste hierarchy describes the process to manage waste. According to Cordella et al. (2019, 3) waste hierarchy aims to reduce waste and avoid disposing waste at landfill. Waste management alternatives can be ranked in chronological order, although small differences in the hierarchies exist (Fercoq, Lamouri & Carbone 2016, 569).

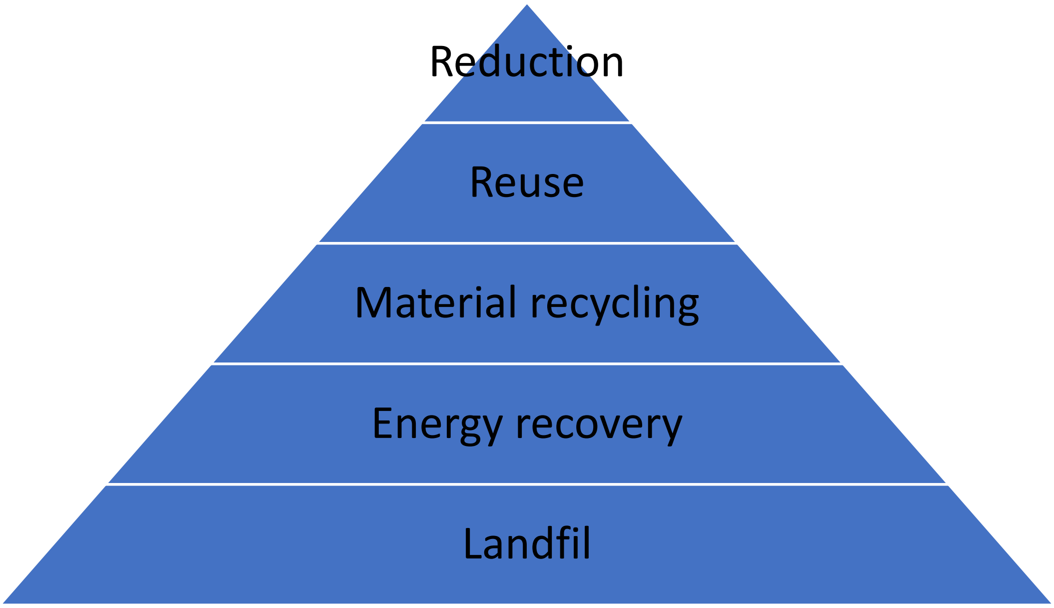

Figure 4. Waste hierarchy (Adapted from Kurdve et al. 2015, 306).

When applying the waste management hierarchy to material efficiency strategies, the main focus should be on waste reduction, which can be achieved by consuming resources efficiently in manufacturing processes (Cordella et al. 2016, 3). Fercoq et al. (2016, 569) state that the focus should be on reducing waste at the source because the total elimination of waste is seen as an unrealistic expectation. According to Sushil (2015, 1) the reduction of waste should be the most important option because it reduces the need for the other waste management phases. According Singh and Sushil (2016, 786) waste generation control during the production can result in a lesser amount of waste to manage, which highlights the importance of waste reduction set by the waste hierarchy.

According to Hyršlová, Vágner & Palásek (2011, 1) material losses result from business processes and they are impossible to separate from material flows. According to Pacelli et al. (2015, 80), the production of scrap cannot be avoided due to limitations related to material, technical or manufacturing issues. Instead, scrap production can be minimized (Pacelli et al. 2015, 80). Shahbazi, Jönsson, Wiktorsson, Kurdve & Bjelkemyr (2018, 24) state that the most economically efficient method is to reduce the generation of scrap in the first place. This way the primary value of material is maintained (Shahbazi, et al. 2018, 24). Schmidt (2010, 555) provides an example on how the value of material is lost when material gets scrapped. In the Schmidt's example, there is a company that every year generates 100 tonnes of aluminium scrap that is then sold in order to gain extra revenue. The price for secondary aluminium is €1,60/kg, which means that the company gains extra revenue worth €160 000 each year. However, all material loss must be first bought at expensive raw material price, which turns the above calculation into loss. The original price for the aluminium was €3/kg, which means that the company has lost €140 000 by selling 100 tonnes of aluminium scrap. Furthermore, material losses lead to additional costs that relate to storing and transporting material losses. Moreover, material losses represent unproductively used labour and capital costs that become wasted while processing material that eventually turns into material loss. These costs can be added in the cost of material losses, which shows the considerable amount that could be used to increase added value by producing products instead of generating material losses. (Schmidt 2010, 555-556)

2.4 Linear and circular production models

According to Cordella et al. (2019, 4) the linear production and consumption model is the worst option in the hierarchy of material efficiency. The linear business model is considered as the traditional manufacturing model that is also referred to as take-make-disposal model (Sariatli 2017, 31). In the linear model, raw materials are processed into products, sold to customers and finally disposed of (Garza-Reyes, Kumar, Batista, Cherrafi & Rocha-Lona 2019, 554). Michelini, Moraes, Cunha, Costa & Ometto (2017, 2) state that the linear production model generates unnecessary waste in many ways such as waste in production processes. According to Sauvé, Bernard, & Sloan (2016, 53) the linear model emphasizes the economic objectives while showing little or no attention for environmental concerns. Thus, the linear model of manufacturing is associated with negative environmental effects (Garza-Reyes et al. 2019, 554).

The linear economy originates from the unequal distribution of wealth where the cost of labour has been inexpensive compared to the cost of input materials. As a result, manufacturers were driven to a use a substantial amount of cheap material and cutting costs on expensive human work. However, the negative side of this system was that it did not put emphasis on waste and ignored waste management activities. (Sariatli 2017, 32) The linear business model is dealing with challenges associated with price volatility and supply risks that result from increased resource scarcity (Garza-Reyes et al. 2019, 554). Michelini et al. (2017, 2) state that, in linear production, only virgin material is put into the value chains. According to Ellen MacArthur Foundation (2013, 14) the linear model exposes companies to risks such as higher resource prices.

The circular economy strives to convert the currently dominating linear system into a circular one with the purpose of realizing much desired material savings (Singh & Ordoñez 2016, 343). In circular economy, waste is returned into productive use (Jones & Comfort 2017, 2). According to Yang, Smart, Kumar, Jolly & Evans (2018, 499) the flow of materials is closed loop in the circular model as shown by figure 5. Geissdoerfer, Savaget, Bocken & Hultink (2017, 5) state that the aim is to prolong the value of the materials as long as possible. In the circular model, the materials put into the system and waste flowing out of the system is minimised (Geissdoerfer et al. 2018, 713).

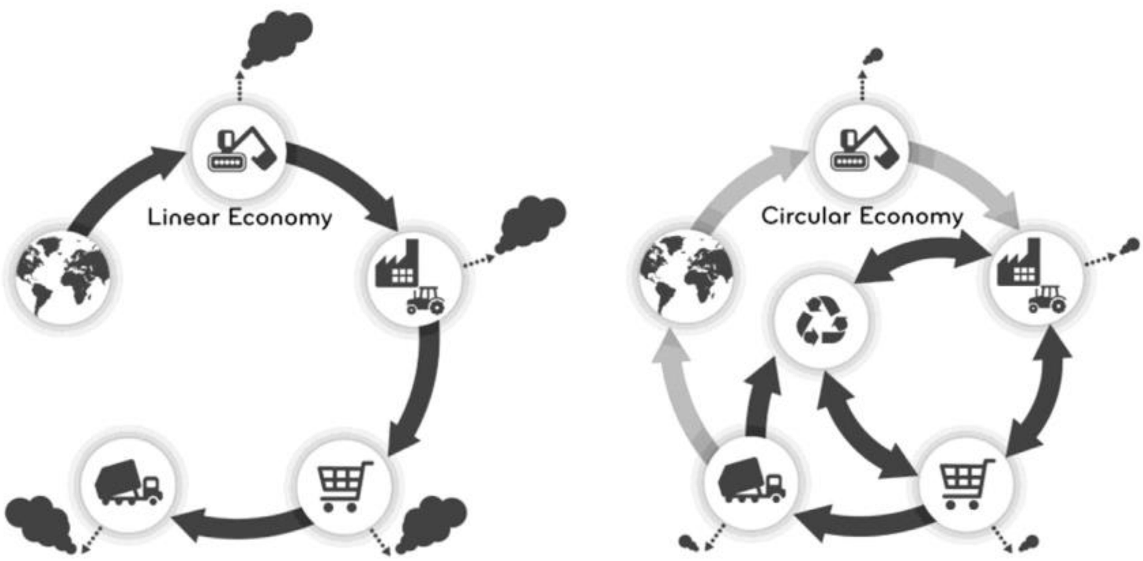

Figure 5. The linear and circular economy models (Sauvé, Bernard & Sloan 2016, 52).

According to Bocken, de Pauw, Bakker & van der Grinten (2016, 309) the approaches to reduce resource use are closing, slowing and narrowing loops. In practise, slowing refers to extending the use of products and reusing products whereas closing refers to recycling of products. Narrowing is associated with reducing the amount of resources needed in products and production processes (Bocken et al. 2016, 310). Geissdoerfer et al. (2018, 713) have added two approaches that are intensifying and dematerialising loops. In practise, intensifying refers to more intense use phase and dematerialisation is associated with service and software solutions to substitute product utility (Geissdoerfer et al. 2018, 713). The expected benefits of circular economy are reduced material waste, which in turn leads to reduced material costs. Thus, organisations adopting circular economy can gain substantial savings by reducing the amount of material input needed. Since resources are used more efficiently in terms of value and volumes, it eventually flattens the cost curve. In addition, the economy is less influenced by price fluctuations of materials. (Sariatli 2017, 33)

2.5 Material efficiency indicators

Kang, Zhao, Li, & Horst (2016, 6333) state that the manufacturing industry has increasingly become competitive, which has highlighted the need for measuring the performance of manufacturing activities. According to Hon (2005, 1) it is crucial for manufacturing companies to measure their performance in order to keep track of the manufacturing's current performance and to implement suitable actions towards maintaining competitiveness. Lindberg, Tan, Yan & Starfelt (2015, 1785) state the industries consists of different kinds of processes that are needed to control in order to reach high levels of performance, The performance measures in manufacturing should monitor the efficiency of manufacturing operations and reflect the manufacturing system's present performance. It is impossible to properly control the efficiency of a process if appropriate measures are not put in place. (Hon 2005, 1)

Brundage, Bernstein, Morris & Horst (2017, 451) state that manufacturing firms use key performance indicators (KPI's) to monitor and improve production performance. According to Wiersema (2014, 29) key performance indicators (KPI's) measure the success of a company. Behrens & Lau (2008, 74) state that companies use KPI's to measure and control company processes and goals. KPI's can be divided into two groups that are financial and non-financial indicators (Behrens & Lau 2008, 74). Mostly used performance indicators relate to costs/ financial, quality, time, delivery reliability and flexibility. Each company must determine their own performance indicators that are relevant to their business. (Ishaq Bhatti, Awan & Razaq 2014, 3129) Typically, KPI's are tracked on a monthly basis (Wiersema 2014, 29).

Lindberg et al. (2015, 1786) state that waste in different forms results in low performance. According to Doorasamy (2016, 283) waste is a result of inefficient production that has an undesirable impact on a company's profitability. According to Lindeberg et al. (2015, 1786) companies can increase their performance through the identification of the waste and executing appropriate actions towards reducing the waste. The figure 6 below proposes different material efficiency KPI's for different categories in a product's lifecycle. The figure shows proposed material efficiency KPI's for residual materials (waste). Blue boxes represent KPI's that are often found in the literature whereas the red boxes show KPI's that are identified through empirical studies. The KPI's in green boxes are less common but still important KPI's for managing waste. The figure shows that scrap generation and cost of scrap are common KPI's used by manufacturing companies to measure waste materials. (Shahbazi et al. 2018, 27)

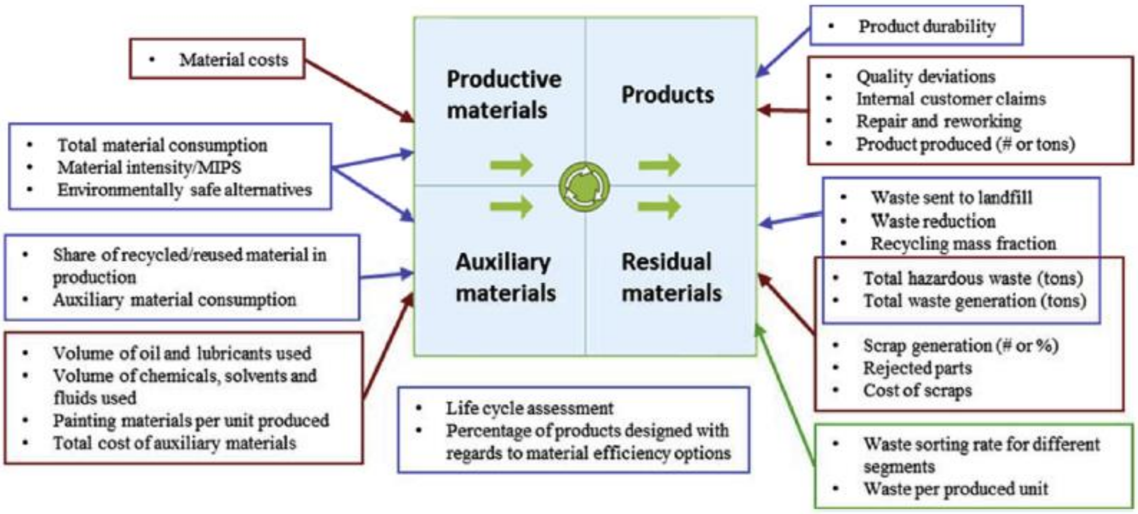

Figure 6. Material efficiency KPI's (Shahbazi et al. 2018, 28)

Financial KPI's have been the best measure to assess the performance of a company throughout the history (Ishaq Bhatti et al. 2014, 3131). Currently companies are mainly interested in material efficiency KPI's that measure financial results such as quality deviations, quality claims and cost of scrap. These KPI's are frequently used due to the high cost of input material and revenues that can be gained by selling metal scrap. (Shahbazi et al. 2018, 27) Ishaq Bhatti et al. (2014, 3131) state that the external stockholders of companies are mostly interested in KPI's that measure the financial performance of a company, which requires companies to incorporate financial measures. According to Worrel, Alwood & Gutowski (2016, 587) businesses are economically driven, and competitiveness plays a key role in the company strategy. Manufacturing companies mostly aim at increasing shareholder value, which requires making improvements in productivity and efficiency but also to reduce costs or increase sales or both (Worrel et al. 2016, 587). Therefore, it is natural for companies to make improvements in these areas (Shahbazi et al. 2018, 29)

3 NESTING PROCESS

This section focuses on presenting the nesting process that is used in manufacturing. In addition, this section describes the basic logic behind nesting. Lastly, it is examined how different raw material sizes impact material utilization in nesting.

3.1 The concept of nesting

According to Niemi (2003, 1549) raw materials are needed to use efficiently in order to reduce costs. According to de Vin, de Vries & Ton Streppel (2000, 4280) an important part of nesting is material utilization. Nesting is applied to decrease the costs of sheet metal cutting. According to Gemmill & Sanders (1991,2521) metal business is one of the industries sharing the problem of cutting parts from stock material as economically as possible. Since material costs are held as a crucial cost factor, it is important to optimize the cutting process (Verlinden, Cattrysse & Oudheusden 2007, 370).

Verlinden et al. (2007, 371) define nesting as positioning many parts of the same material on a sheet or metal plate in such a way that the remaining waste material is minimized. Nesting is utilized to find the most optimum solution for utilizing the sheet when cutting parts with different shapes from it (Babu & Babu 1999, 1625). The problem related to placing parts on a metal sheet or plate in such a way that the amount of material loss is minimized is called the nesting problem (Niemi 2013, 1549) The nesting problem is part of cutting and packing (C&P) problems in which big objects are divided into smaller with the objective of minimizing the unused areas of the big object. Typically, these unused areas are designated as waste. (Toledo, Carravilla, Ribeiro, Oliveira & Gomes 2013, 478) The common logical structure of cutting and packing problems is shown by figure 7 below. In summary, the structure of C&P problems consists of the following:

- large objects (input) defined in geometric dimensions
- small items (output) defined in geometric dimensions

The set of small items are grouped into one or more subgroups and allocated on the area of the large object in such a way that

- The selected small items are placed inside the large object.
- The small items cannot overlap. (Wäscher, Hausner & Schumann 2007, 1110)

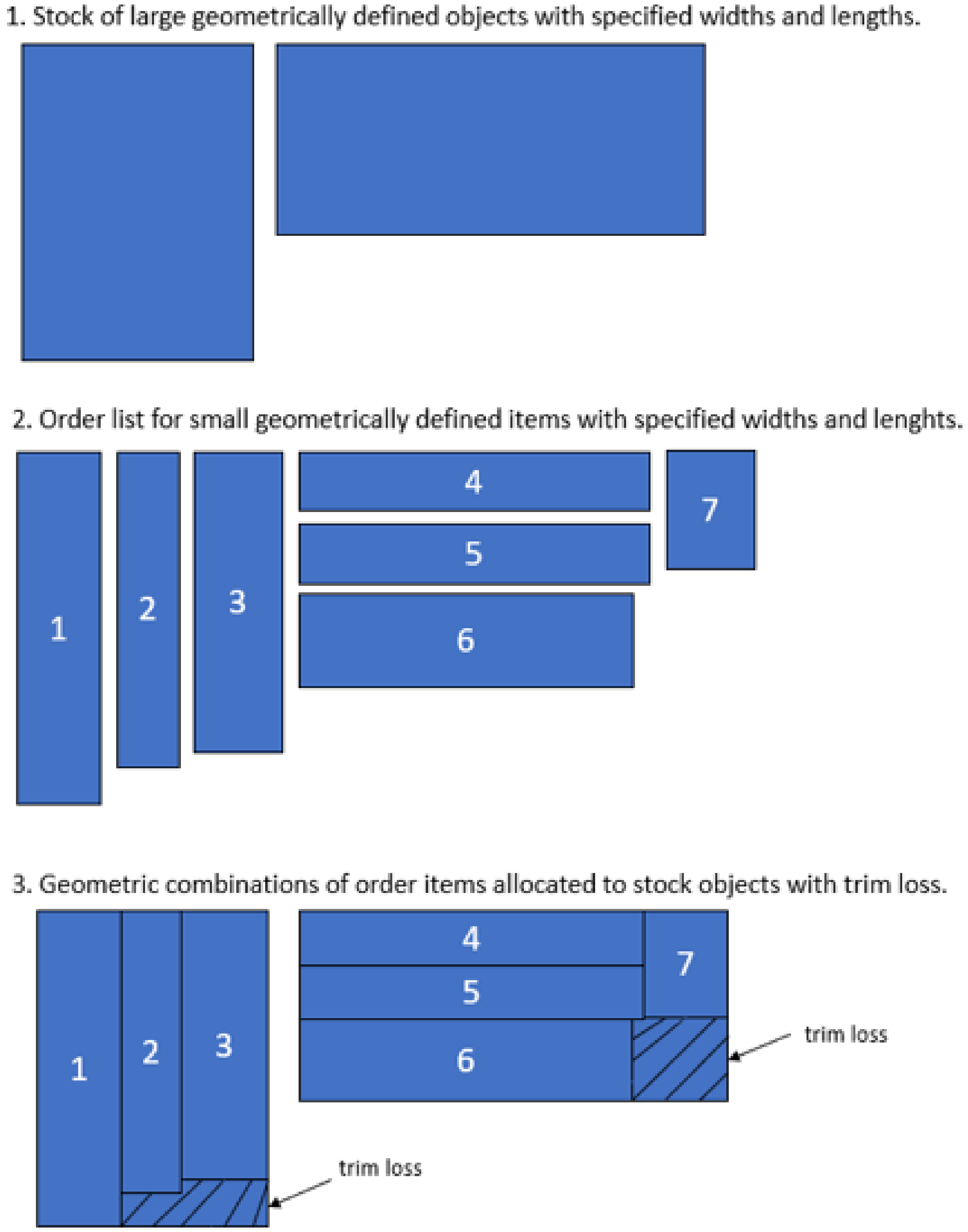

Figure 7. Illustration of the structure of cutting problems (Adapted from Dyckhoff 1990, 145)

According to Lam, Sze and Tan (2007, 169) efficient nesting can minimise the quantity of scrap and reduce costs significantly. According to Niemi (2003, 1549) nesting is conducted via computer to create solutions called as nesting layouts or cutting patterns, that are to minimize the material waste. Nesting is carried out by using a nesting software system to reduce waste and to improve production efficiency (Xie & Xu 2008, 25-26). The nesting software aims for efficiency by automatically arranging the required parts of the sheet or plate by using advanced mathematical algorithms. The main function of a nesting software is that it is able to control a cutting machine by a functional code. (Weston, 2008)

3.2 The effect of raw material size in nesting

Iles (2011) states that nesting alone cannot improve material utilization if the parts cut from plates are mostly large in size. According to Kannan (2010) material utilization in nesting can be optimized by choosing the right sheet size. According to Schneider et al. (2013, 122) material efficiency can be increased by optimizing raw material sizes purchased. According to Agrawal 1(993, 424) the size of the sheet is a factor that contributes to the generation of trim loss. According to Kanawaty (1992, 192), in metal sheet cutting operations a technique to improve yield is to change the original size of the raw material.

Schneider et al. (2013, 122) state that the use of wrong sheet dimensions in production may lead to significantly increased scrap rates. The use of wrong sheet size can have a negative consequence to the cost of the product since material utilization is not the same for the same set of parts on different sheet sizes (Kanawaty 1992, 192). Thus, the use of wrong sheet size can have a destructive effect on the cost of the product. Especially, the selection of the right sheet size becomes crucial for assemblies that include multiple parts. (Kannan 2010) Poorly sized sheet material complicates material part flow, which in turn increases costs (Iles, 2011)

Gasimov, Sipahioglu, & Saraç, (2007, 64) state that the selection of the most optimal combination of material sizes to be hold in the stock in order to minimize an appropriate function is known as the assortment problem. According Iles (2011) it is important to purchase sheet material in sizes that generate the lowest amount of scrap. Erjavec, Gradisar & Trkman (2012, 170) state that trim loss is dependable on the sizes selected to be hold in the stock. Pentico (2008, 295) states that it is more economical to choose only a subset of different sizes rather than choosing each size available to be hold in the stock due to limitations related to storage, manufacturing or holding costs related to storing different sizes in the stock.

4 MATERIAL FLOW COST ACCOUNTING

This chapter is focused on presenting MFCA. This section begins with an introduction to MFCA, which is followed by an overview of the history and development of the concept. The third part presents the difference between traditional cost accounting and MFCA and finally, the MFCA procedure is presented.

4.1 The concept of MFCA

Companies are seen as a system of material flows (Hyršlová et al. 2011,5). This system is concerned with generating added value by transforming purchased input materials into final products that are delivered to customers. In an ideal production, all inputs would be transformed into products without the generation of waste. (Guenther, Jasch, Schmidt, Wagner & Ilg 2015, 1250) Christ & Burritt (2017, 603) suggest that MFCA refers to the idea that each material leaves a company either in the form of a final product or in the form of waste.

MFCA is used to identify how much material losses result from a product or production process (Nakajima, Kimura & Wagner 2015, 1303). MFCA identifies all input materials that flow through a manufacturing process as well as the produced output in both final products and material losses. The finished products are referred to as positive products whereas waste is referred to as negative products or non-product outputs. MFCA visualizes the costs associated with producing material losses, which is to show improvement possibilities. (Takakuwa, Zhao & Ichimura 2014, 45) This is done by quantifying material flows in physical and monetary units (Sygulla, Bierer, Götze, 2011, 3).

Doorasamy & Garbharran (2015, 71) state that MFCA is a part of environmental management accounting. MFCA is a type of accounting associated with resource efficiency and achieving cost savings (Yagi & Kokubu 2018, 763). Schmidt (2015, 1310) states that the purpose of MFCA is to recognise possibilities for monetary savings, which is realized by avoiding the generation of all non-productive material flows such as waste. Typically, the saving potential is presented in monetary terms because cost related issues are important to manufacturing companies (Schmidt 2015, 1310).

4.2 The development of MFCA

The development of MFCA began in the 1990’s due to emerging environment management systems. At the time, there was a growing interest towards materials flows, waste and sustainability that were driven by the need for protecting the environment and growing material costs. (Schmidt et al. 2013, 2) These systems promoted the growing economic and environmental interest towards reducing operational material and energy inputs (Schmidt & Nakajima 2013, 360). According to Doorasamy & Garbharran (2015, 73) a few trial projects regarding MFCA was developed in Germany in the 1990’s. MFCA was first developed under the name flow cost accounting in Germany (Christ & Burritt 2015, 1380).

In 2000, MFCA was adopted to Japan where it became a popular tool to asses material losses in both physical and monetary units (Doorasamy & Garbharran 2015, 73). According to Christ & Burritt (2015, 1380) The Japanese Ministry of economy became interested in MFCA due to its potential practical relevance to tackle concerns in manufacturing and began to support the use of MFCA to be applied in companies in Japan. According to Schmidt & Nakajima (2013, 360) there are nowadays more than 300 companies in Japan using MFCA.

In 2007, it was suggested by Japan to integrate MFCA to the ISO 14000 family in order to support companies worldwide to adopt more efficient resource management (Doorasamy & Rhodes 2017, 104). Many countries alongside Japan and Germany participated in developing the MFCA to be part of ISO standard. In 2011, MFCA was published under the ISO standard 14501. (Schmidt & Nakajima 2013, 360-361) The ISO 14051 aims to provide the general framework for MFCA including for instance objectives, principles and the implementation process (Christ & Burritt 2015, 1380).

4.3 The difference between MFCA and conventional cost accounting

According to Kokobu & Nakajima (2004, 4) conventional cost accounting methods do not provide enough information regarding the cost of material losses. In general, conventional cost accounting does not show whether raw material is turned into products or discarded as waste (Huang, Chiu, Chao & Wang 2019, 6). It is not generally required in conventional cost accounting to determine whether material ends up as product or waste. Instead, the conventional accounting is interested in determining whether the sales revenue can cover the costs incurred. (Kokubu & Kitada 2010, 4) In conventional cost accounting the incurred material losses are invisible because the product covers all costs. In the contrary, MFCA treats costs separately, which makes material losses transparent (Schmidt et al. 2013, 1233).

Table 1. The difference between cost accounting and MCFA (Adapted from Papaspyropoulos, Karamanolis, Sokos & Birtsas 2016, 327)

Cost category	Cost Accounting method	
	Conventional	Material Flow
Sales	15 000€	15 000€
Production cost	**4 500€**	**3000€**
Material loss cost	-	**1 500€**
Gross profit	10 500€	10 500€
Other expenses	8 000€	8 000€
Operating profit	2 500€	2 500€

The difference between conventional cost accounting and MFCA is shown in table 1 below. As illustrated by the table 1 all the costs are assigned to the product costs in conventional cost accounting even though it can be seen in the MFCA that one third of the materials consumed are transformed into waste. Thus, the costs of the material are not seen by the managers. In the contrary, MFCA allocates the costs of the produced waste to material losses. This allows managers to better manage costs and gain cost savings. (Papaspyropoulos et al. 2016, 327) In general, companies are aware of the input material of each process and the output generated from the input in terms of products produced. However, the amount of material losses generated per each process tends to remain unknown. (Schmidt & Nakajima 2013, 363) By making a difference between produced product costs and waste costs, MFCA aims to show how much monetary value is lost with waste. This way MFCA aims to encourage the management to reduce waste generation and improve business efficiency (Huang et al. 2019, 6).

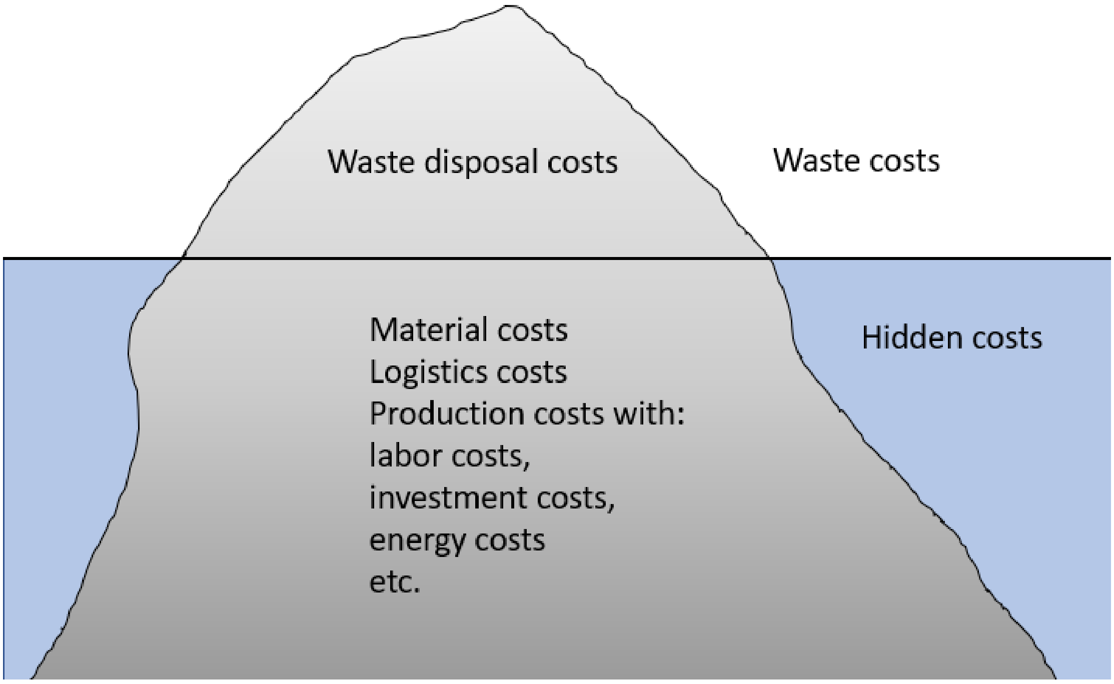

Figure 8. Costs of waste (Adapted from Schmidt 2010, 555)

Huang et al. (2019, 5) state that the cost of waste is considered as the hidden cost since the costs of waste is typically overlooked by conventional cost accounting. According to Wan et al. (2015, 603) the hidden costs represent the unused inputs that are included in the waste streams. The figure 8 provided by Schmidt (2010, 555) shows the visible and hidden costs of materials turned into waste. As shown by the figure, the direct costs of waste disposal are visible to companies. However, there are several other costs associated with waste, such as material costs, that remain invisible. Schmidt (2010, 555) states that hidden costs are typically associated with inefficiencies. According to Huang et al. (2019, 5) it is a matter of importance for companies to reduce the hidden costs in order to improve financial performance.

4.4 MFCA procedure

Christ & Burritt (2014, 4) state that the current literature presents the implementation process of MFCA in a consistent manner apart from small differences in expressions used and variances in system boundaries utilized. The first step of MFCA is to step create a material flow model. The flow model is an illustration of organisational processes, which helps to understand the material flows inside a company. (Christ & Burritt 2015, 1381) Material flows are defined as material movements between quantity centers. In MFCA the material movements are divided between material flows and material loss flows. (Sugylla et al. 2011, 3) In order to develop a material flow model, the system boundaries, quantity centres and material flows are needed to be identified (Sugylla et al 2011, 3). According to Schmidt et al (2013, 234) system boundaries can refer to processes, the whole organisation or the supply chain. Quantity centers are often referred to as processes, which are used for quantifying materials in physical and monetary terms (Kokobu & Tachikawa 2013, 356).) According to Kokubu &. Tachikawa (2015, 356) the quantity centers can be based on information derived for instance from cost centers or other existing information. The figure 9 below shows an illustration of the material flows in MFCA. Input refers to material or energy that has been put to the quantity center whereas output refers to finished products and waste that leave the quantity center. The quantity center refers to manufacturing. The term product refers to any product that can be considered as the final product whereas material loss refers material that was not transformed into final product. (Hyršlová et al. 2011, 6)

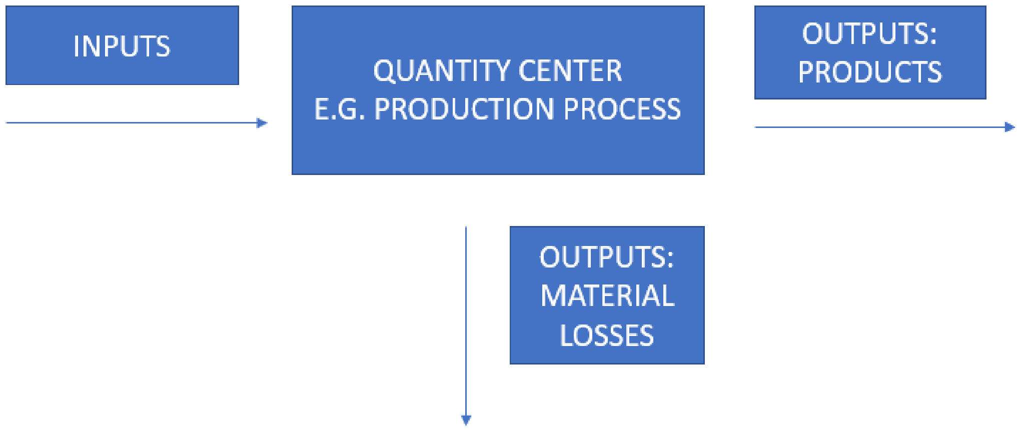

Figure 9. MFCA chart (Adapted from Hyršlová, Vágner, Palásek 2011, 7)

Once the flow model has been developed, the next step is to quantify the determined material flows. To realize this, each material movement is measured within an individual quantity center within a defined period. (Sugylla et al. 2011, 3) The identified material flows need to be quantified on physical units (Schmidt et al 2013, 235). It is recommended to use a single mass unit such as kilogram for quantifying material flows (Sugylla et al. 2011, 3). The idea is to create a material balance by allocating values to the flow model (Christ & Burritt 2015, 1381). Material flow balance aims to recognise how much of the input material is put into the system and how much of input material is transformed into product and waste (Doorasamy 2016, 271). The physical inputs put into the process should be equal to the outputs manufactured from the process since mass cannot be created or destroyed, only transformed (Christ & Burritt 2015, 1381). Huang et al. (2019, 4) state that input material should equal to the quantity of finished products including both positive products (finished goods) and negative products (produced waste). According to Sugylla et al. (2011, 3) a balance is formulated in order to ensure that every material movement is quantified. According to Kokubu & Tachikawa (2013, 352) the following equations is used to measure all input materials, product and material losses in physical units: Input = Products + Material loss. The figure 10 below presents an example of a typical material balance. This example shows that a total of 100 kg consisting of materials A, B, C, D and E are put into the operations. These input materials are allocated between product (70kg) and material losses (30kg). (Kokubu & Tachikawa 2013, 356)

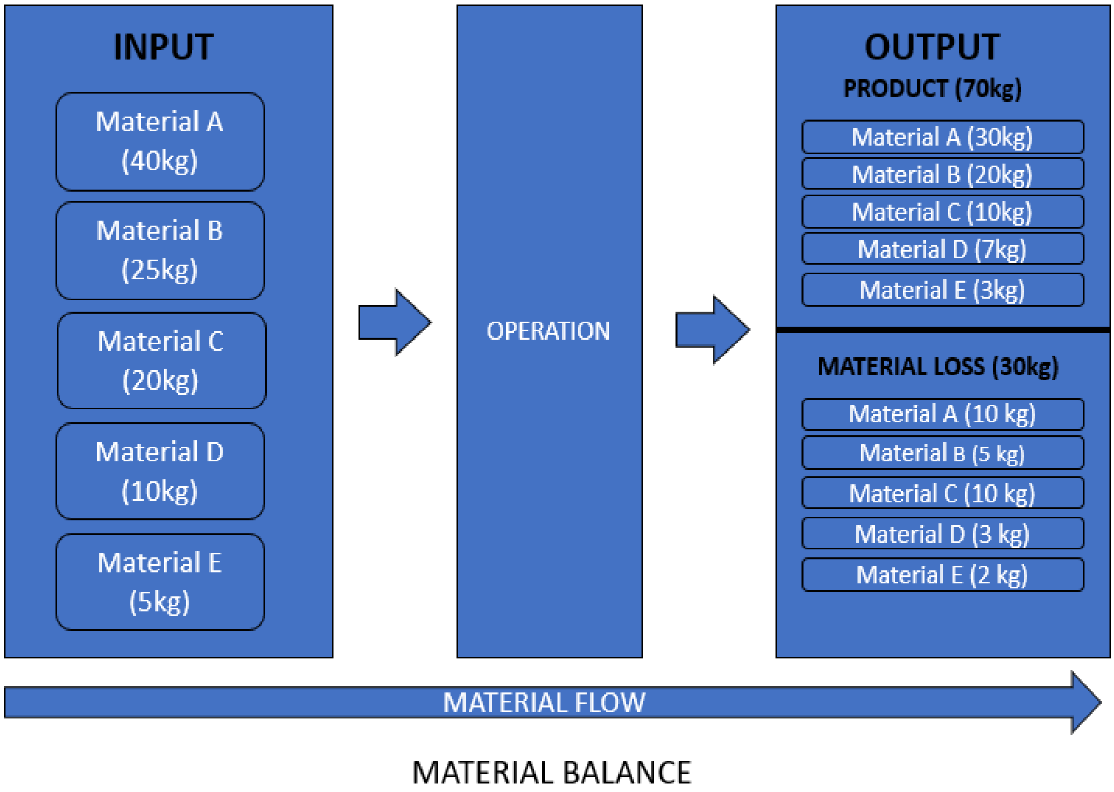

Figure 10. Illustration of material balance (Adapted from Kokubu & Tachikawa 2013, 357)

Since companies usually require financial information in order to make decision, the monetary value of the material losses is calculated (Kokubu & Tachikawa 2013, 353). After tracing down the material flows, the incurred costs can be calculated (Kokubu & Kitada, 2015 1280). According to Sygulla et al (2011, 3) MFCA focuses on four cost categories that are material, energy, system and waste management costs. Material costs can be calculated by using the following formula: physical amount of material x material input price (Sygulla et al. 2011, 3). Usually the purchase costs of the input material in considered as the material cost (Kokobu & Tachikawa 2013, 353). According to Doorasamy & Garbharran (74, 2015) the material purchase value of non-product output motivates companies to gain savings. Even though it is possible to sell the material loss to a recycling company, it can recover only a small part of the material value (Doorasamy & Garbharran 72, 2015). The figure 11 shows that 100kg of material enters the production process and the produced output is divided between 80kg of product output and 20kg of waste output. In this example, processing costs are also taken into account along the material costs. The costs calculated for the input material are $1,000 which is further divided according to the weight ratio between product and waste, into $800 and $200, The processing cost ($120) is also allocated to the wastes according to the weight ratio of 20% .Thus, the total cost of the waste is $320. (Kokubu & Kitada 2010, 5, 8)

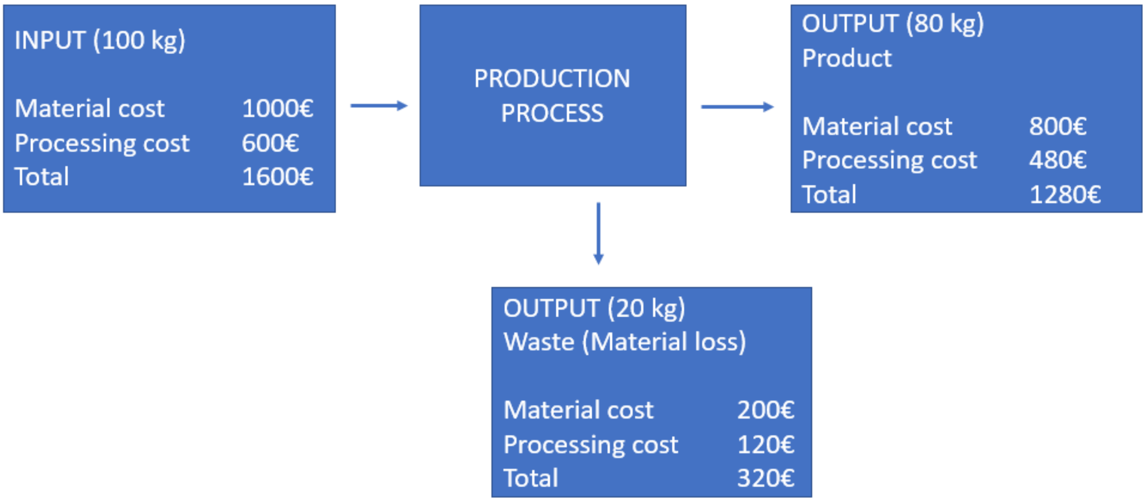

Figure 11. An example of cost calculation in MFCA (Adapted from Kokubu & Kitada 2010, 26)

The last step of the MFCA process is to summarise, assess and interpret the MFCA results (Christ& Burritt 2014, 5). This can be done for instance by using material flow cost matrices. The results should be evaluated in order to determine whether there are improvement opportunities related to reducing waste. (Schmidt et al 2013, 235) According to Kokubu & Tachikawa (2013, 360) the summarised data points out material losses that are environmentally or financially considerable. After the results are evaluated, companies should take appropriate actions towards improvement opportunities. Furthermore, it is important that the data is shared to the relevant stakeholders who are involved with the cost/quantity centres included in the MFCA. Lastly, it is essential to monitor the material flows and the associated costs on regular basis. (Christ & Burritt 2015, 1382)

5 RESEARCH METHDOLOGY

This chapter aims to present the research methodology of this thesis. This chapter starts by introducing the case after which the research methods, data collection and sampling are presented. Lastly the samples are analysed by descriptive statistics.

5.1 Introduction of the case

The case company of this study is a manufacturing company that supplies composite beams for the construction sector. This study concentrates on evaluating the material efficiency of different metal sheet and plate sizes that are used as raw material in the beam manufacturing. The beams can be manufactured in any size because they are made on project basis. Thus, the case company uses different sheet and plate sizes in order to control the scrap generated.

The beam manufacturing was chosen for material efficiency assessment because it could provide considerable savings in terms of scrap generation. Since scrap represents the monetary value lost, it is important to reduce the generation of scrap in order to improve economic performance. Metal sheets and plates where chosen as a raw material for this study because they represent one of the biggest raw material groups used by the case company. Thus, it is expected to gain savings in this raw material group.

The target process under assessment is the nesting process of the beam production. Nesting is carried out before the metal parts of the beams are cut in order to maximize the efficient use of the raw material by reducing the amount of scrap generated. Nesting process was selected under assessment because nesting is the point at which the scrap is generated.

In this study, the aim is to compare the scrap generated per each sheet and plate sizes selected for this research. As a result, the generation of scrap should be reduced as well as the monetary value associated with the scrap. In addition, the plate sizes can be optimized based on the comparisons. The sizes selected for this research are further described and discussed in chapter 5.4.

5.2 Research methods

This thesis is a single case study. This study involves collecting specific and intensive information about the case under study. A case study can examine a single case, situation or a group of cases. The case is often studied within its natural setting. (Hirsjärvi et al (2009, 134-135) Case study method was chosen for this thesis because the method enables the author to gain an in-depth understanding about the phenomena under study. According to Shahbazi et al. (2018, 19) case study should be chosen when there is not much information available related to a certain topic. Material efficiency in the manufacturing context has not been studied much and therefore there is limited knowledge available related to the topic. (Shahbazi et al. 2018, 14)

The research approach chosen for this thesis is quantitative approach. According to (Vilkka 2007, 14) quantitative research method is focused on numerical data, which means that that the research data is examined in a numerical form. According to Williams (2007, 65) quantitative approach is usually chosen when responds are needed to be given in a numerical form. In quantitative research, both data collection and data analysis deals with numeric data and mathematical models. (Williams, 2007, 66) In a quantitative research, the researcher presents that research results in numbers. The researcher interprets and explains the numeric results. (Vilkka 2007, 14) According to Heikkilä (2018, 16) the aim of quantitative research is to generalize results by statistical conclusions. Quantitative approach was chosen for this thesis because this thesis deals with numeric data. Moreover, the results are shown in numbers.

Quantitative research often uses deductive reasoning, which means that the starting point is from theory to practise. In deductive approach the aim is to draw specific conclusions based on theory. Thus, deductive research proceeds from theory to empirical part, which is the reason why deductive approach is often referred to as theory-based research. (Kananen 2010, 40, 76). This research uses deductive reasoning since the aim is to make conclusion based on theory.

5.3 Data collection

This research is based on secondary data collection. According to Hirsjärvi et al. (2009, 186) secondary data refers to data that has been collected by someone else than the researcher. Vilkka (2007, 33) defines secondary data as material that is collected for instance from statistics, databases, articles and from other publications. In quantitative research, all information is valid if it can be measured or changed to a measurable form either before or after the data collection (Vilkka 2007, 30-31). According to Heikkilä (2008, 18) in quantitative research, data can be collected for instance from statistics.

Secondary data was collected for the empirical part. The data for the MFCA calculations was collected from nesting reports that were obtained from the case company's nesting software's statistics. It was agreed together with the case company to use secondary data for the calculations because it is a less time-consuming way to conduct this research. Moreover, it was the only feasible way to conduct this research at the time. The case company conducted the collection of the nesting reports from the statistics.

The nesting reports contain a nesting summary regarding each nested sheet or plate such as data regarding the used plate, plate utilisation, order parts, and machine times. From each report, the researcher collected the sheet/ plate dimensions, nest% and the need year of the nest. The reports are from years 2014-2019 from which most of them are from years 2018-2019.

From each report, the researcher moved manually the required information from each report into excel in order to transform the data into workable form. In addition to the nesting statistics, metal plate purchase prices and data regarding the consumption of different metal plate sizes was also collected from the case company.

5.4 Sampling

Sample is a defined portion of a population (Tuomi 141, 2007). Population can refer to people, total quantity of things or cases from which the samples are selected (Etikan, Musa & Alkassim 1, 2016). There are many ways to conduct the selection of a sample (Tuomi 141, 2007). The sampling of this research is based on quota sampling in which the population is divided into subgroups that represent the population being studied. In quota sampling, it is required to predetermine the number of units selected for each subgroup. Only the number of sampling units determined by the quota is included in each subgroup. (Holopainen & Pulkkinen 2013, 36-37) Tables 2-5 show the different categories being compared and the subgroups under each category. The subgroups consist of different sheet and plate dimensions that represent the chosen categories. The sheets are metal thickness of 5mm – 6mm and plates refer metal thickness of 8mm-30m.

Table 2. Sample size of the width of 1500mm and 2000mm

Width 1500mm	**Sample size**	**Width 2000mm**	**Sample size**
6x1500x8000	30	6x2000x8000	30
5x1500x10000	30	5x2000x10000	30
6x1500x10000	30	6x2000x10000	30
8x1500x10000	30	8x2000x10000	30
5x1500x12000	30	5x2000x12000	30
6x1500x12000	30	6x2000x12000	30
8x1500x12000	30	8x2000x12000	30
Total	210	**Total**	210

Table 3. Sample sizes of the width of 2000mm and 2070mm

Width 2000mm	**Sample size**	**Width 2070mm**	**Sample size**
8x2000x10000	30	8x2070x10000	30
8x2000x12000	30	8x2070x12000	29
Total	60	**Total**	59

Table 4. Sample sizes of the lengths of 10000mm and 11000mm

Length 10000mm	**Sample size**	**Length 11000mm**	**Sample size**
25x2000x10000	30	20x2000x11000	30
20x2000x10000	30	25x2000x11000	30
Total	60	**Total**	60

Table 5. Sample size of the lengths of 12000mm and 13500mm

Length 12000mm	**Sample size**	**Length 13500mm**	**Sample size**
5x2000x12000	30	5x2000x13500	30
6x2000x12000	30	6x2000x13500	30
8x2000x12000	30	8x2000x13500	30
10x2000x12000	8	10x2000x13500	30
12x2000x12000	30	12x2000x13500	30
15x2000x12000	30	15x2000x13500	30
20x2000x12000	30	20x2000x13500	30
25x2000x12000	30	25x2000x13500	30
30x2000x12000	30	30x2000x13500	30
Total	248	**Total**	270

As shown by the tables above, the aim was to obtain a quota of 30 units per each sub-group. According to Vilkka (2007,57) the sample size should consist of at least 30 units if the aim is to compare different groups. However, this quota was not fulfilled by two dimensions. In the case of the subgroup of 10x2000x12000, it was not possible to obtain more nests from the statistics leaving the sample size containing only 8 units.

5.5 Descriptive statistics

Descriptive statistics was used to analyse the collected data, which was conducted by using Excel. Descriptive analysis aims to provide a description of the data in a clear way (Hodeghatta & Nayak 2017, 62). Descriptive statistics is used in this thesis to analyse the collected data because a large set of numbers is required to present in a simple way.

According to Vilkka (2007, 119, 121) mean is a one of the most used central tendency measures that aim to describe where the majority of the cases are likely to fall in the distribution. Arithmetic mean is calculated by adding up the values, which is then divided by the number of the values (Vilkka 2007, 122). Descriptive statistics was used to calculate the average nest% and scrap % of the samples. Since the scrap % was not readily available information, the author calculated the scrap% for each sheet and plate nested included in the samples by using the following formula:

100% (plate area) – nest % (plate area used for order parts) = scrap % (unused area).

Table 6 shows the average nest% and average scrap % calculated for each sheet and plate dimensions.

Table 6. Average nest% and scrap %

Size	Average nest %	Average scrap %
6x1500x8000	86,68	13,32
5x1500x10000	88,00	12,00
6x1500x10000	85,74	14,27
8x1500x10000	86,47	13,53
5x1500x12000	86,22	13,78
6x1500x12000	84,28	15,72
8x1500x12000	86,32	13,68
6x2000x8000	87,64	12,36
5x2000x10000	88,93	11,07
6x2000x10000	88,75	11,25
8x2000x10000	87,16	12,84
20x2000x10000	91,14	8,86
25x2000x10000	90,90	9,11
20x2000x11000	86,95	13,05
25x2000x11000	84,57	15,43
5x2000x12000	89,39	10,61
6x2000x12000	89,89	10,11
8x2000x12000	85,95	14,05
10x2000x12000	86,96	13,04
12x2000x12000	88,96	11,04
15x2000x12000	90,24	9,76
20x2000x12000	90,79	9,21
25x2000x12000	89,35	10,65
30x2000x12000	90,03	9,97
5x2000x13500	87,69	12,31
6x2000x13500	88,39	11,61
8x2000x13500	87,92	12,08
10x2000x13500	92,22	7,78
12x2000x13500	91,33	8,67
15x2000x13500	90,43	9,57
20x2000x13500	91,69	8,31
25x2000x13500	88,31	11,69
30x2000x13500	91,49	8,51
8x2070x10000	87,71	12,29
8x2070x12000	84,72	15,28

However, the weakness of mean is that it can be easily affected by values that differ from the typical values. For instance, mean does not provide precise distribution if the data set contains a value that is very low or high compared to the normal values.

Thus, it is recommended to use dispersion measures to describe the scattering of the data. (Vilkka 2007, 123)

Table 7. Dispersion measures of the mean

Size (mm)	Average scrap %	Standard deviation	Standard error	Sample size
6x1500x8000	13,32	3,32	0,61	30
5x1500x10000	12,00	2,91	0,53	30
6x1500x10000	14,27	3,20	0,58	30
8x1500x10000	13,53	5,58	1,02	30
5x1500x12000	13,78	3,41	0,62	30
6x1500x12000	15,72	9,19	1,68	30
8x1500x12000	13,68	5,00	0,91	30
6x2000x8000	12,36	3,08	0,56	30
5x2000x10000	11,07	2,14	0,39	30
6x2000x10000	11,25	3,17	0,58	30
8x2000x10000	12,84	4,53	0,83	30
20x2000x10000	8,86	2,40	0,44	30
25x2000x10000	9,11	3,03	0,55	30
20x2000x11000	13,05	5,94	1,08	30
25x2000x11000	15,43	6,60	1,20	30
5x2000x12000	10,61	2,46	0,45	30
6x2000x12000	10,11	2,50	0,46	30
8x2000x12000	14,05	5,08	0,93	30
10x2000x12000	13,04	3,96	1,40	8
12x2000x12000	11,04	3,17	0,58	30
15x2000x12000	9,76	2,77	0,51	30
20x2000x12000	9,21	2,41	0,44	30
25x2000x12000	10,65	4,03	0,74	30
30x2000x12000	9,97	2,83	0,52	30
5x2000x13500	12,31	4,37	0,80	30
6x2000x13500	11,61	3,29	0,60	30
8x2000x13500	12,08	3,87	0,71	30
10x2000x13500	7,78	3,08	0,56	30
12x2000x13500	8,67	4,00	0,73	30
15x2000x13500	9,57	3,90	0,71	30
20x2000x13500	8,31	3,40	0,62	30
25x2000x13500	11,69	3,41	0,62	30
30x2000x13500	8,51	4,16	0,76	30
8x2070x10000	12,29	4,34	0,79	30
8x2070x12000	15,28	4,25	0,79	29

Table 7 shows the standard deviation and standard error calculated for each sample. Standard deviation is used to describe the dispersion of a single value by describing how far away the value is from the calculated average value of the data set (Vilkka 2007, 124). The standard error describes the accuracy of the mean and it is influenced by the standard deviation and the sample size (Heikkilä 88, 2008). The standard deviation of each sample shows that the samples are heterogeneous since the individual values within each sample are scattered to some extent around the sample means. The standard error shows that the sample means are likely deviate to some extent from the population means.

6 IMPLEMENTATION OF THE EMPIRICAL PART

The sixth chapter is focused on calculating the material losses with the use of MFCA. MFCA analysis was chosen as a method for analysis because the aim is to assess material losses of different metal sheet and plate sizes generated from the nesting process. This chapter follows the procedure of MFCA that consists of agreeing the system boundary, developing the flow structure, quantifying the physical amount of material flows and quantifying the physical values in monetary terms. The last part of this chapter presents the results regarding the differences in material efficiency between different sheet and plate sizes.

Due to confidential information, the physical and monetary values presented in this version are fictional.

6.1 The system boundary

Before the material flow model can be established it is necessary to agree the system boundary. The system boundary is limited to a single process that is the nesting process of the beam production. The nesting process is conducted before the cutting process in order to maximize the material utilization of the selected raw material. Even though the waste generated does not become tangible in nesting, it is the point at which the utilization of raw material is planned. Thus, nesting is considered in this study to represent the point of waste generation since waste generation can be controlled at this step.

6.2 Material flow model of the nesting process

After the system boundary has been agreed, the second step is to identify the material flows of the selected process. Thus, the nesting process represents the quantity centre which is the measuring point of the material flows. The focus is on raw material in the form of metal sheets and plates. This raw material category was chosen because it is one of the main raw material groups used by the case company. Thus, it is expected to gain savings in this material group.

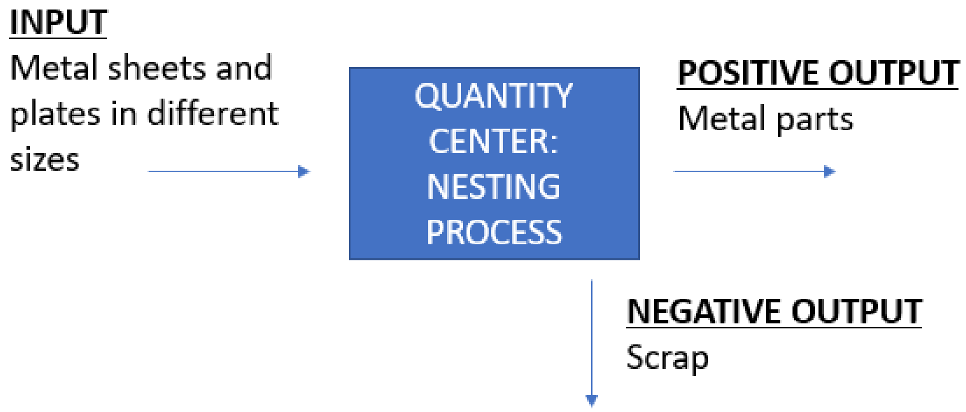

Figure 12. Material flow model of the nesting process.

Figure 12 shows the illustration of the identified material flows of the nesting process. As mentioned before, the input material used in the nesting process are metal sheets and plates in different sizes that differ in width, length and thickness. In this study, metal sheets represents metal thicknesses of 5-6mm whereas metal plates represent thicknesses of 8-30mm. In nesting, material efficiency can be controlled by the size of the raw material. In practise this is done by selecting the correct sheet or plate size that generates the minimum amount of scrap.

The nesting process generates two types of output material flows. These are metal parts of the beams and metal scrap. Metal parts are considered as positive product because metal parts are desirable output generated from the process. In the contrary, metal scrap is regarded as negative product because metal scrap is undesirable output from the system.

The figure 13 represents an example of the nesting process related to the case company's beam manufacturing. The numbered parts are metal parts that are needed in the production. These metal parts represent desirable output. These parts are placed on the plate in such a way that the amount of scrap is reduced to minimum in order to increase material efficiency.

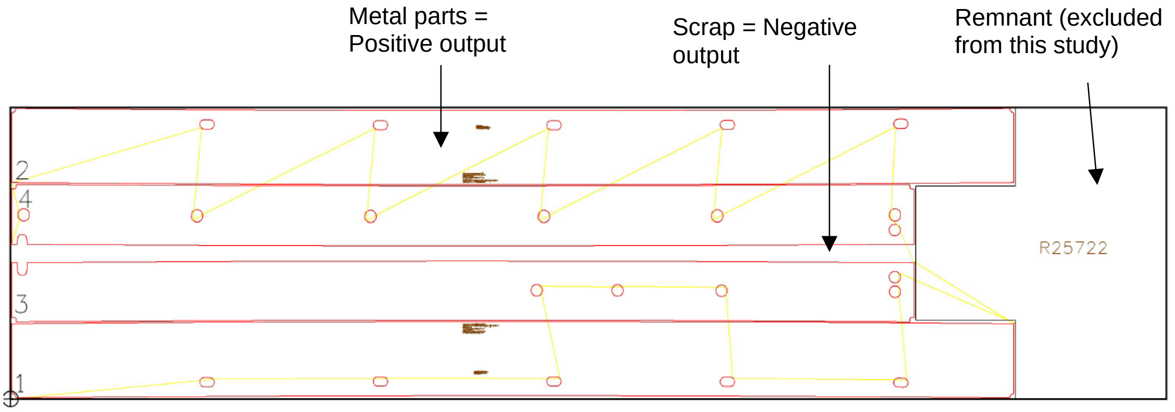

Figure 13. An example of the case company's nesting process (Source: case company’s nesting report)

In the figure, the large numbered part on the right side of the plate is a remnant that is another type of waste that can be stocked and reused in production. As mentioned in the limitations, remnants are excluded from this research.

The unused area between the numbered parts is scrap material that this study is focused on. The problem with metal scrap is that it cannot be used again in the production of the case company and thus, the metal scrap is sold to a recycling company. Another problem associated with metal scrap is that it ties up capital of the case company. Even though scrap can be sold, the revenues gained from selling the scrap are smaller compared to the original purchase value of the sheets and plates. The generated amount of scrap represents the physical and monetary value that could have been used to manufacture the order parts. Raw materials are one of the biggest cost factors of the case company, which is typical for companies in the manufacturing sector. Therefore, it is desirable to minimize the amount of scrap generated in the process in order gain financial savings.

6.3 Quantification of the physical units

The third step of MFCA is to quantify the identified material flows. Next the identified material flows of the previous section are quantified in physical units in order to visualize how much of the input material is transformed into positive and negative output flows. The distinction between the output flows is made in order to understand how much of the input material ends up as waste that is the core principle of MFCA. Table 8 below presents the quantification of the physical units. The values in the table represent average values. The values are rounded to the nearest whole number.

The very first column in the left lists all the sizes included in the size categories. The second Input column shows how much input material (metal sheet or plate size) was put into the system. The unit of mass used in the calculations is kilograms (kg). The input kg represents the average weekly consumption of the respective metal sheet or plate size. Thus, the reference period of the measurement is a week. The average input kg's were only known for the sizes that are mainly used by the case company, but for comparison reasons the input kg's were applied to the non-standard sizes as well. The input amount equals to 100% that is then divided between positive and negative output.

Table 8. Quantification of physical units

	Input		Positive output		Negative output	
Size (mm)	**Kg**	**%**	**kg**	**%**	**Kg**	**%**
6x1500x8000	704	100	610	86,68	94	13,32
6x2000x8000	704	100	617	87,64	87	12,36
5x1500x10000	357	100	315	88	43	12
6x1500x10000	704	100	604	85,74	100	14,27
8x1500x10000	348	100	301	86,47	47	13,53
5x2000x10000	357	100	318	88,93	40	11,07
6x2000x10000	704	100	625	88,75	79	11,25
8x2000x10000	348	100	304	87,16	45	12,84
8x2070x10000	348	100	305	87,71	43	12,29
5x1500x12000	369	100	318	86,22	51	13,78
6x1500x12000	293	100	247	84,28	46	15,72
8x1500x12000	392	100	338	86,32	54	13,68
5x2000x12000	369	100	329	89,39	39	10,61
6x2000x12000	293	100	263	89,89	30	10,11
8x2000x12000	392	100	337	85,95	55	14,05
8x2070x12000	392	100	332	84,72	60	15,28
20x2000x10000	952	100	867	91,14	84	8,86
25x2000x10000	505	100	459	90,9	46	9,11
20x2000x11000	952	100	828	86,95	124	13,05
25x2000x11000	505	100	427	84,57	78	15,43
5x2000x12000	369	100	329	89,39	39	10,61
6x2000x12000	293	100	263	89,89	30	10,11
8x2000x12000	392	100	337	85,95	55	14,05
10x2000x12000	202	100	176	86,96	26	13,04
12x2000x12000	192	100	171	88,96	21	11,04
15x2000x12000	401	100	362	90,24	39	9,76
20x2000x12000	481	100	437	90,79	44	9,21
25x2000x12000	325	100	291	89,35	35	10,65
30x2000x12000	407	100	366	90,03	41	9,97
5x2000x13500	369	100	323	87,69	45	12,31
6x2000x13500	293	100	259	88,39	34	11,61
8x2000x13500	392	100	344	87,92	47	12,08
10x2000x13500	202	100	186	92,22	16	7,78
12x2000x13500	192	100	175	91,33	17	8,67
15x2000x13500	401	100	363	90,43	38	9,57
20x2000x13500	481	100	441	91,69	40	8,31
25x2000x13500	325	100	287	88,31	38	11,69
30x2000x13500	407	100	372	91,49	35	8,51

The column in the middle presents the positive output. This column shows how much positive output (metal parts) was produced from the system per week. The amount of positive output was collected from each nesting report in the form of nest% that refers to the area of the metal plate used for producing the metal parts. Once the average nest % was calculated for each size, it was possible to calculate the amount of positive output in kilograms by using the following formula:

Positive output kg = Input kg x Nest%

The last column on the right side represent the negative output that refers to scrap. The scrap % was not readily available information on the nesting reports. Thus, the amount of scrap (%) per each nested sheet/ plate was calculated by using the following formula:

Scrap %= Input % (100%) – Positive output%

Once the average scrap % was known, the average amount of scrap in kg was calculated by using the following equation:

Negative output kg = Input kg x Scrap%

The quantification of the scrap generated per each sheet and plate size shows the case company how much input material ends up as material loss. The material loss presents the amount of input material that could have been saved to manufacture final products. Thus, the generated material loss represent inefficiency in processes that should motivate the case company to reduce the generation of scrap.

6.4 Quantification of monetary value

The third step of MFCA procedure includes the quantification of the monetary value of the material flows. This section shows the monetary value associated with physical values of the identified material flows calculated in the previous section. This step reveals the so-called hidden values of the waste that are usually ignored by the traditional cost accounting. Although there are four different cost categories in MFCA, this study is only focused on direct material costs that refer to the purchase cost of the input material that flows through the process. Thus, the monetary quantification of this step shows how much savings could be gained in financial losses.

Table 9. Metal plate purchase prices

Width	**Thickness**	**€/ kg**
1500mm	all	0,129
2000mm	5mm-6mm	0,144
2000mm	8mm-30mm	0,123

Table 9 shows the purchase prices of the sheets and plates. These prices are used for calculating the monetary value of the material flows. Table 10 shows the quantification of the monetary values. The monetary value is represented in euros (€) and the values are calculated for each material flow including input and output flows. As in the previous section, the reference period is week and the costs of the output flows equal to the cost of the input material flow. The monetary values of the material flows are calculated by using the following formula:

Material costs = Physical amount of material x material input price

The values in table 10 are rounded to the nearest whole number in order to present the values in a clear way.

Table 10. Quantification of monetary value

	Input			Positive output			Negative output		
Size (mm)	**Kg**	**€**	**%**	**kg**	**€**	**%**	**Kg**	**€**	**%**
6x1500x8000	704	91	100	610	79	86,68	94	12	13,32
6x2000x8000	704	101	100	617	89	87,64	87	12	12,36
5x1500x10000	357	46	100	315	41	88	43	6	12
6x1500x10000	704	91	100	604	78	85,74	100	13	14,27
8x1500x10000	348	45	100	301	39	86,47	47	6	13,53
5x2000x10000	357	51	100	318	46	88,93	40	6	11,07
6x2000x10000	704	101	100	625	90	88,75	79	11	11,25
8x2000x10000	348	43	100	304	37	87,16	45	5	12,84
8x2070x10000	348	43	100	305	38	87,71	43	5	12,29
5x1500x12000	369	48	100	318	41	86,22	51	7	13,78
6x1500x12000	293	38	100	247	32	84,28	46	6	15,72
8x1500x12000	392	51	100	338	44	86,32	54	7	13,68
5x2000x12000	369	53	100	329	47	89,39	39	6	10,61
6x2000x12000	293	42	100	263	38	89,89	30	4	10,11
8x2000x12000	392	48	100	337	41	85,95	55	7	14,05
8x2070x12000	392	48	100	332	41	84,72	60	7	15,28
20x2000x10000	952	117	100	867	107	91,14	84	10	8,86
25x2000x10000	505	62	100	459	56	90,9	46	6	9,11
20x2000x11000	952	117	100	828	102	86,95	124	15	13,05
25x2000x11000	505	62	100	427	53	84,57	78	10	15,43
5x2000x12000	369	53	100	329	47	89,39	39	6	10,61
6x2000x12000	293	42	100	263	38	89,89	30	4	10,11
8x2000x12000	392	48	100	337	41	85,95	55	7	14,05
10x2000x12000	202	25	100	176	22	86,96	26	3	13,04
12x2000x12000	192	24	100	171	21	88,96	21	3	11,04
15x2000x12000	401	49	100	362	45	90,24	39	5	9,76
20x2000x12000	481	59	100	437	54	90,79	44	5	9,21
25x2000x12000	325	40	100	291	36	89,35	35	4	10,65
30x2000x12000	407	50	100	366	45	90,03	41	5	9,97
5x2000x13500	369	53	100	323	46	87,69	45	7	12,31
6x2000x13500	293	42	100	259	37	88,39	34	5	11,61
8x2000x13500	392	48	100	344	42	87,92	47	6	12,08
10x2000x13500	202	25	100	186	23	92,22	16	2	7,78
12x2000x13500	192	24	100	175	22	91,33	17	2	8,67
15x2000x13500	401	49	100	363	45	90,43	38	5	9,57
20x2000x13500	481	59	100	441	54	91,69	40	5	8,31
25x2000x13500	325	40	100	287	35	88,31	38	5	11,69
30x2000x13500	407	50	100	372	46	91,49	35	4	8,51

The calculation of the monetary value shows the case company how much capital is associated with the scrap generated. The monetary value of the scrap generated has a negative impact on the case company profitability. Thus, the calculation of the monetary value should motivate the case company to improve their financial performance.

6.5 Results of the differences in material efficiency

This section compares the scrap generation of the metal sheet and plate dimensions calculated in the previous chapter. The scrap generation is compared in both physical and monetary terms. The comparison shows the difference in scrap generated per week and year. Scrap generation per year is calculated by multiplying the scrap kg and scrap € by the number of weeks in a year (52 weeks).

6.5.1 Comparison between the widths of 1500mm and 2000mm

In this section, the comparison of sheet and plates is made between the widths of 1500mm and 2000mm. The width of 2000mm represents the standard dimension whereas the width of 1500 is a non-standard dimension. This section consists of five different comparisons meaning that from both width categories, five plate dimensions (thickness x width x length) are selected for comparison. Lastly, the summary of the material efficiency of the selected width categories is provided and compared.

Table 11. Comparison between 6x1500x8000 and 6x2000x8000

	Scrap %	**Scrap/ week**		**Scrap/ year**	
Size (mm)	**%**	**Kg**	**€**	**Kg**	**€**
6x1500x8000	13,32	94	12	4 875	629
6x2000x8000	12,36	87	12	4 527	650
Difference	0,96	7	0	348	-21

Table 11 shows that size of 6x2000x8000 shows greater material efficiency compared to the size of 6x1500x8000. The scrap % is 12,36% in the width of

2000mm whereas the scrap % is 13,32% in the width of 1500mm. The difference in material efficiency between the widths is 0,96%, which translates into material savings of 348kg per year. However, the width of 1500mm is more cost-efficient in terms of scrap generated compared to the width of 2000mm. The monetary difference in material efficiency is 21€ per year.

Table 12. Comparison between 5x1500x10000 and. 5x2000x10000

	Scrap %	**Scrap/ week**		**Scrap/ year**	
Size (mm)	**%**	**Kg**	**€**	**Kg**	**€**
5x1500x10000	12	43	6	2231	288
5x2000x10000	11,07	40	6	2059	295
Difference	0,93	3	0	172	-8

Table 12 shows that the size of 5x2000x10000 shows greater material efficiency compared to the size of 5x1500x10000. The scrap % of the size of 5x1500x10000 is 11,07% whereas the scrap % of the size of 5x1500x10000 is 12%. The difference in material efficiency between the widths is 0,93%, which translates into yearly material savings of 172kg. However, the width of 1500mm is more cost-efficient in terms of scrap generated compared to the width of 2000mm. The monetary difference in material efficiency is 8 € per year.

Table 13. Comparison between 6x1500x10000 and 6x2000x10000

	Scrap %	**Scrap/ week**		**Scrap/ year**	
Size (mm)	**%**	**Kg**	**€**	**Kg**	**€**
6x1500x10000	14,27	100	13	5221	674
6x2000x10000	11,25	79	11	4118	591
Difference	3,02	21	2	1 102	82

Table 13 shows that the size of 6x2000x10000 shows greater material efficiency compared to the width of 6x1500x10000. The scrap% is 11,25% in the width of 2000mm whereas the scrap % is 14,27% in the width of 1500mm. The difference in material efficiency between the widths is 3,02%. The material savings are 1 102 kg per year. The width of 2000mm is also more cost-efficient in terms of scrap generated compared to the size of 1500mm. The yearly savings in material costs are 82€.

Table 14. Comparison between 8x1500x10000 and 8x2000x10000

	Scrap %	Scrap/ week		Scrap/ year	
Size (mm)	**%**	**Kg**	**€**	**Kg**	**€**
8x1500x10000	13,53	47	6	2449	316
8x2000x10000	12,84	45	5	2324	286
Difference	0,69	2	1	125	30

Table 14 shows that the size of 8x2000x10000 shows greater material efficiency compared to the size of 8x1500x10000. The scrap % is 12,84% in the width of 2000mm whereas the scrap % is 13,53% in the width of 1500mm. The difference in material efficiency is 0,69%, which translates into material savings of 125 kg per year. The width of 2000mm is also more cost-efficient in terms of scrap generated compared to the width of 1500mm. The monetary savings in material cost are 30€ per year.

Table 15. Comparison between 5x1500x12000 and 5x2000x12000

	Scrap %	Scrap/ week		Scrap/ year	
Size (mm)	**%**	**Kg**	**€**	**Kg**	**€**
5x1500x12000	13,78	51	7	2642	341
5x2000x12000	10,61	39	6	2033	292
Difference	3,17	12	1	608	49

Table 15 shows that the size of 5x2000x12000 shows greater material efficiency compared to the size of 5x1500x12000. The scrap % is 10,61% in the width of 2000mm whereas the scrap % is 13,78% in the width of 1500mm. The difference in material efficiency is 3,17%, which translates into material savings of 608 kg per year. The width of 2000mm is also more cost-efficient in terms of scrap generated. The yearly savings in material costs are 49€.

Table 16. Comparison between 6x1500x12000 and 6x2000x12000

	Scrap %	Scrap/ week		Scrap/ year	
Size (mm)	**%**	**Kg**	**€**	**Kg**	**€**
6x1500x12000	15,72	46,05	5,94	2 395	309
6x2000x12000	10,11	29,60	4,25	1 539	221
Difference	5,61	16	2	855	88

Table 16 shows that the size of 6x2000x12000 shows greater material efficiency compared to the size of 6x1500x12000. The scrap % is 10,11% in the width of 2000mm whereas the scrap% is 15,72% in the width of 1500mm. The difference in material efficiency is 5,61%. This translates into material savings of 855 kg per year. The width of 2000mm is also more cost-efficient in terms of scrap generated compared to the width of 1500mm. The yearly savings in material cost are 88€.

Table 17. Comparison between 8x1500x12000 and 8x2000x12000

	Scrap %	Scrap/ week		Scrap/ year	
Size (mm)	**%**	**Kg**	**€**	**Kg**	**€**
8x1500x12000	13,68	54	7	2787	359
8x2000x12000	14,05	55	7	2860	352
Difference	-0,37	-1	0	-73	7

Table 17 shows that the size of 8x1500x12000 shows greater material efficiency compared to the size of 8x2000x12000. The scrap % is 13,68% in the width of 2000 whereas the scrap% is 14,05% in the width of 1500mm. The difference in material efficiency is 0,37%, which translates into yearly material savings of 73 kg. However, the width of 2000mm is more cost-efficient in terms of scrap generated. The yearly savings in material costs are 7€.

Table 18. Comparison between the widths of 1500mm and 2000mm

Width	Scrap %	Scrap kg/ year	Scrap €/ year
1 500mm	13,76	22 599	2 915
2 000mm	11,76	19 461	2 687
Difference	2	3 138	228

Table 18 shows the total amount of scrap generated in physical and monetary units per year in the widths of 1500mm and 2000mm. The results show that in total the width of 2000m generates less scrap compared to the width of 1500mm. The scrap generation in the width of 2000mm is on average 11,76% whereas the scrap generation in the width of 1500mm is 13,76%. The difference in scrap generation between the widths is on average 2%. The material savings are 3 138 per year and the monetary savings in scrap 228€ per year in the width of 2000mm.

If the material efficiency of the width of 1500mm was improved, the input price of the width of 1500mm should be decreased in order to gain savings on financial losses. Given the results, this means that the total scrap generated in the width of 1500mm (22 599kg) should cost the same as the total scrap generated in the width of 2000mm (2 687€). Thus, the cost of the total monetary value of scrap generated in the width of 2000mm is divided by the physical amount of scrap generated in the width of 1500mm. Thus, the formula to calculate the target unit price for the width of 1500mm is the following:

2 687 €/ 22 599kg = 0,119€/kg

The difference between the current price and the target price is the following:

0,129€ /kg (current unit price)- 0,119€/kg (target unit price) = 0,01€

The result shows that the target price should be 0,119€/kg in order to get the same financial result as in the scrap generated in the width of 2000mm. The difference between the current price and target price is about 0,01€.

6.5.2 Comparison between the widths of 2000mm and 2070mm

In this section, the comparison of sheet and plates is made between the widths of 2000mm and 2070mm. The width of 2000mm represents the standard dimension whereas the width of 2070mm is a non-standard dimension. This section consists of two different comparisons meaning that from both width category, two plate dimensions are selected for comparison. Lastly, the summary of the material efficiency of the selected width categories is provided and compared.

Table 19. Comparison between 8x2000x10000 and 8x2070x10000

	Scrap %	Scrap/ week		Scrap/ year	
Size (mm)	**%**	**Kg**	**€**	**Kg**	**€**
8x2000x10000	12,84	45	5	2324	286
8x2070x10000	12,29	43	5	2226	274
Difference	0,55	2	0	99	12

Table 19 shows that the size of 8x2070x10000 shows greater material efficiency compared to the size of 8x2000x10000. The scrap generation in the size of 8x2070x10000 is 12,29% whereas the scrap generation in the size of 8x2000x10000 is 12,84%. The difference in material efficiency between the widths is 0,55%. This translates into material savings of 99kg per year and the savings in material costs are 12€ per year.

Table 20. Comparison between 8x2000x12000 and 8x2070x12000

	Scrap %	Scrap per week		Scrap per year	
Size (mm)	**%**	**Kg**	**€**	**Kg**	**€**
8x2000x12000	14,05	55	7	2860	352
8x2070x12000	15,28	60	7	3112	383
Difference	-1,23	-5	-1	-252	-31

Table 20 shows that the size of 8x2000x12000 shows greater material efficiency compared to the size of 8x2070x12000. The scrap generation in the width of 2000mm is 14,05% whereas the scrap generation is 15,28% in the width of 2070mm. The difference in material efficiency is 1,23%. This translates into material savings of 252kg per year and material cost savings of 31€ per year.

Table 21. Comparison between the widths of 2000mm and 2070mm

Width (mm)	Scrap %	Scrap kg/ year	Scrap €/ year
2 000	13,45	5 184	638
2 070	13,79	5 338	656
Difference	-0,34	-153	-19

Table 21 shows the total amount of scrap generated in physical and monetary units per year in the widths of 2000mm and 2070mm. The results show that in total the width of 2000m generates less scrap compared to the width of 2070mm. The difference in scrap generation is 0,34% between the widths. The material savings are on average 153 kg per year and the yearly monetary savings in scrap are 19€.

6.5.3 Comparison between the lengths of 10000mm and 11000mm

In this section, the comparison of sheet and plates is made between the widths of 10000mm and 11000mm. The length of 10000mm represents the standard dimension whereas the length of 11000mm is a non-standard length. This section consists of two different comparisons meaning that from both length category, two plate dimensions are selected for comparison. Lastly, the summary of the material efficiency of the selected length categories is provided and compared.

Table 22. Comparison between 20x2000x10000 and 20x2000x11000

	Scrap %	**Scrap/ week**		**Scrap/ year**	
Size (mm)	**%**	**Kg**	**€**	**Kg**	**€**
20x2000x10000	8,86	84	10	4384	539
20x2000x11000	13,05	124	15	6458	794
Difference	-4,19	-40	-5	-2 075	-255

Table 22 shows that the size of 20x2000x10000 shows greater material efficiency compared to the size of 20x2000x11000. The scrap generation in the length of 10000mm is 8,86% whereas the scrap generation in the length of 11000mm is 13,05%. The difference in material efficiency between the lengths is 4,19%. This translates into yearly material savings of 2 075kg and yearly material cost savings of 255€.

Table 23. Comparison between 25x2000x10000 and 25x2000x11000

	Scrap %	**Scrap/ week**		**Scrap/ year**	
Size (mm)	**%**	**Kg**	**€**	**Kg**	**€**
25x2000x10000	9,11	46	6	2392	294
25x2000x11000	15,43	78	10	4053	498
Difference	-6,32	-32	-4	-1 661	-204

Table 23 shows that the size of 25x2000x10000 shows greater material efficiency compared to the size of 25x2000x11000. The scrap generation in the length of

10000mm is 9,11% whereas the scrap generation in the length of 11000mm is 15,43%. The difference in scrap % between the lengths is 6,32%. This translates into yearly material savings of 1 661kg and yearly material cost savings of 204€.

Table 24. Comparison between the lengths of 10000mm and 11000mm

Length (mm)	Scrap %	Scrap kg/year	Scrap €/year
10 000	8,99	6 776	834
11 000	14,24	10 512	1 293
Difference	-5,26	-3 736	-459

Table 24 shows the total amount of scrap generated per year in the lengths of 10000mm and 11000mm. The results show that in total the length of 10 000 generates less scrap compared to the length of 11000mm. On average the scrap generated in the length of 10 000mm is 8,98% whereas the scrap generation in the length of 11 000mm is 14,24%. The difference in scrap generation is 5,26% between the lengths. The material savings are 3 736kg per year and the monetary saving in scrap is 459€ per year.

6.5.4 Comparison between the lengths of 12000mm and 13500mm

This section compares the sheet and plates lengths of 12000mm and 13500mm. The length of 12000mm represents the standard dimension whereas the length of 13500mm is a non-standard length. This section consists of nine different comparisons meaning that from both length category, nine plate dimensions are selected for comparison. Lastly, the summary of the material efficiency of the selected length categories is provided and compared.

Table 25. Comparison between 5x2000x12000 and 5x2000x13500

	Scrap %	Scrap/ week		Scrap/ year	
Size (mm)	**%**	**Kg**	**€**	**Kg**	**€**
5x2000x12000	10,61	39	6	2033	292
5x2000x13500	12,31	45	7	2358	339
Difference	-1,70	-6	-1	-325	-47

Table 25 shows that the size of 5x2000x12000 shows greater material efficiency compared to the size of 5x2000x13500. The scrap generation in the length of 12000mm is 10,61% whereas the scrap generation in the length of 13500mm is 12,31%. The difference in scrap % between the lengths is 1,70%. This translates into material savings of 325kg per year and material cost savings of 47€ per year.

Table 26. Comparison between 6x2000x12000 and 6x2000x13500

	Scrap %	**Scrap/ week**		**Scrap/ year**	
Size (mm)	**%**	**Kg**	**€**	**Kg**	**€**
6x2000x12000	10,11	30	4	1539	221
6x2000x13500	11,61	34	5	1768	254
Difference	-1,50	-4	-1	-229	-33

Table 26 shows that the size of 6x2000x12000 shows greater material efficiency compared to the size of 6x2000x13500. The scrap generation in the length of 12000mm is 10,11% whereas the scrap % in the length of 13500mm is 11,61%. The difference in scrap % between the lengths is 1,50%. The material savings per year are 229kg per year and the material cost savings per year are 33€.

Table 27. Comparison between 8x2000x12000 and 8x2000x13500

	Scrap %	**Scrap/ week**		**Scrap/ year**	
Size (mm)	**%**	**Kg**	**€**	**Kg**	**€**
8x2000x12000	14,05	55	7	2860	352
8x2000x13500	12,08	47	6	2460	303
Difference	1,97	8	1	400	49

Table 27 shows that the size of 8x2000x13500 shows greater material efficiency compared to the size of 8x2000x12000. The scrap generation in the length of 13500mm is 12,08% whereas the scrap % in the length of 12000mm is 14,05%. The difference in scrap % is 1,97%. The material savings per year are 400 kg and the material cost savings per year are 49€.

Table 28. Comparison between 10x2000x12000 and 10x2000x13500

	Scrap %	Scrap/ week		Scrap/ year	
Size (mm)	**%**	**Kg**	**€**	**Kg**	**€**
10x2000x12000	13,04	26	3	1370	169
10x2000x13500	7,78	16	2	816	101
Difference	5,26	11	1	554	68

Table 28 shows that size of 10x2000x13500 shows greater material efficiency compared to the size of 10x2000x12000. The scrap % in the length of 13500mm is 7,78% whereas the scrap generation in the length of 12000mm is 13,04%. The difference in scrap % is 5,26%. The material savings per year are 554 kg and the material cost savings are 68€ per year.

Table 29. Comparison between 12x2000x12000 and 12x2000x13500

	Scrap %	Scrap/ week		Scrap/ year	
Size (mm)	**%**	**Kg**	**€**	**Kg**	**€**
12x2000x12000	11,04	21	3	1102	135
12x2000x13500	8,67	17	2	866	106
Difference	2,37	5	1	237	29

Table 29 shows that size of 12x2000x13500 shows greater material efficiency compared to the size of 12x2000x12000. The scrap generation in the length of 13500mm is 8,67% whereas the scrap generation is 11,04% in the length of 12000mm. The difference in scrap % between the lengths is 2,37%. The material savings are 237 kg per year and the material cost savings are 29€ per year.

Table 30. Comparison between 15x2000x12000 and 15x2000x13500

	Scrap %	Scrap/ week		Scrap/ year	
Size (mm)	**%**	**Kg**	**€**	**Kg**	**€**
15x2000x12000	9,76	39	5	2036	250
15x2000x13500	9,57	38	5	1997	246
Difference	0,19	1	0	39	5

Table 30 shows that the size of 15x2000x13500 shows greater material efficiency compared to the size of 15x2000x12000. The scrap generation in the length of 13500mm is 9,57% and the scrap% is 9,76% in the length of 12000mm. The difference in scrap % is 0,19% between the lengths. The material savings per year are 39 kg per year and the material cost savings are 5 € per year.

Table 31. Comparison between 20x2000x12000 and 20x2000x13500

	Scrap %	Scrap/ week		Scrap/ year	
Size (mm)	**%**	**Kg**	**€**	**Kg**	**€**
20x2000x12000	9,21	44	5	2306	284
20x2000x13500	8,31	40	5	2080	256
Difference	0,90	4	1	226	28

Table 31 shows that the size of 20x2000x13500 shows greater material efficiency compared to the size of 20x2000x13500. The scrap generation is 8,31% in the length of 13500mm whereas the scrap % is 9,21% in the length of 12000mm. The difference in scrap % is 0,90%. The material savings per year are 226 kg and the material cost savings are 28€ per year.

Table 32. Comparison between 25x2000x12000 and 25x2000x13500

	Scrap %	Scrap/ week		Scrap/ year	
Size (mm)	**%**	**Kg**	**€**	**Kg**	**€**
25x2000x12000	10,65	35	4	1802	222
25x2000x13500	11,69	38	5	1976	243
Difference	-1,04	-3	0	-174	-22

Table 32 shows that the size of 25x2000x12000 shows greater material efficiency compared to the size of 25x2000x13500. The scrap generation in the length of 12000mm is 10,65% whereas the scrap % in the length of 13500mm is 11,69%. The difference in scrap % is 1,04%. The material savings are 174 kg per year and the material cost savings are 22€ per year.

Table 33. Comparison between 30x2000x12000 and 30x2000x13500

	Scrap %	Scrap/ week		Scrap/ year	
Size (mm)	**%**	**Kg**	**€**	**Kg**	**€**
30x2000x12000	9,97	41	5	2106	259
30x2000x13500	8,51	35	4	1799	221
Difference	1,46	6	1	307	38

Table 33 shows that the size of 30x2000x13500 shows greater material efficiency compared to the size of 30x2000x12000. The scrap generation in the length of 13500mm is 8,51% whereas the scrap% in the length of 12000mm is 9,97%. The difference in scrap % between the lengths is 1,45%. The material savings per year are 307 kg and the material cost savings per year are 38€.

Table 34. Comparison of the lengths of 12000mm and 13500mm

Length (mm)	Scrap %	Scrap kg/ year	Scrap €/ year
12000mm	10,94	17 155	2184
13500mm	10,06	16 120	2068
Difference	**0,88**	**1 035**	**116**

Table 34 shows the total amount of scrap generated per year in the lengths of 12000mm and 13500mm. The results show that in total the length of 13500mm generates less scrap compared to the length of 12000mm. The scrap generation in the length of 13500mm is 10,06% whereas the scrap % is 10,94% in the length of 12000mm. The difference in scrap generation is 0,88% between the lengths. The material savings per year are 1 035 kg and the monetary saving per year in scrap are 116 €.

6.5.5 Summary of the results

Table 35 shows a summary regarding the differences in material efficiency between different sheet and plate sized measured in both physical and monetary units. The results show that the width of 2000mm is more material efficient compared to the width of 1500mm. The difference in scrap generation between the widths is 2%. In physical units, the difference is 3 138kg per year. The monetary difference between the widths is 228€ per year. The results show that the width of 2000mm should be used instead of 1500mm.

Table 35. Summary of the differences in material efficiency between the size categories

Width (mm)	Scrap %	Scrap kg/ year	Scrap €/ year
1 500mm	13,76	22 599	2 915
2 000mm	11,76	19 461	2 687
Difference	**2**	**3 138**	**228**
Width (mm)	**Scrap %**	**Scrap kg/ year**	**Scrap €/ year**
2 000	13,45	5 184	638
2 070	13,79	5 338	656
Difference	**-0,34**	**-153**	**-19**
Length (mm)	**Scrap %**	**Scrap kg/ year**	**Scrap €/ year**
10 000	8,99	6 776	834
11 000	14,24	10 512	1 293
Difference	**-5,26**	**-3 736**	**-459**
Length (mm)	**Scrap %**	**Scrap kg/ year**	**Scrap €/ year**
12000mm	11	17 155	2 184
13500mm	10,06	16 120	2 068
Difference	**0,88**	**1 035**	**116**

In the second comparison between the widths of 2000mm and 2070mm, the material efficiency is slightly greater in the width of 2000mm compared to the width of 2070mm. The difference between the widths is only 0,34%. In physical units, the difference is about 153kg per year. In monetary terms the difference is 19€ per year. Based on the comparison, the width of 2000mm should be used instead of the width of 2070mm.

The third category compares the lengths of 10 000mm and 11 000mm. In this comparison, the length of 10 000mm shows greater material efficiency compared to the width of 11 000mm, the difference being 5,26%. In physical terms, the difference is 3 736 kg per year. The difference in monetary value is 459€ per year. Thus, the length of 10 000mm should be used instead of the length of 11000mm.

The fourth comparison between the widths of 12000mm and 13500mm, shows that the length of 13500mm is more efficient in terms material utilization. The difference in material efficiency is 0,88% The difference in physical amount of scrap generated is 1035 kg per year and the difference in monetary value is 116€ per year. Based on the results, the length of 13500mm should be used instead of the length of 12000mm.

7 DISCUSSION AND CONCLUSIONS

The final chapter of this thesis starts by discussing the significance of the results by mirroring the results through theory. After that the answers are given to the research questions that were set for this study. The third part of this chapter evaluates the reliability and validity of this thesis after which the managerial recommendations are given. Lastly, this chapter provides future research suggestions.

7.1 The comparison between theoretical and empirical findings

According to Tajelawi & Garbharran (2015, 3767-3768) MFCA was originally developed to support environmental related decisions with the purpose of increasing resource efficiency and at the same time improving economic and environmental performance of companies. Even though the environmental aspect is an important part of MFCA, the perspective of this study was mainly on the monetary value of the waste generated rather than on the environmental side since cost related factors matter. As stated by Shahbazi et al. (2018, 27) manufacturing companies are mostly interested in material efficiency KPI's that measure financial information rather than improving environmental performance. Thus, the idea that economic and environmental benefits can be achieved simultaneously has not been understood completely. According to Tajelawi & Garbharran (2015, 3786) MFCA has not gained much of popularity amongst companies.

However, it is natural that companies are driven by financial matters over environmental issues since it is important for companies to make profit. Thus, instead of increasing material efficiency by reducing waste in processes, companies show more motivation towards maximizing the number of products produced in order to obtain more revenues. As stated by Doorasamy & Garbharran (2015, 73) companies are generally interested in the amount of products manufactured from inputs rather than on material losses generated from a process. According to Kokobu & Kitada (2010, 10) the main purpose of a company is to maximize profits, which creates a conflict between the environmental objectives of MFCA and company's financial objectives. Since managers are responsible for making profits, it is usual that companies put importance on means that increase profits in the future if the alternative strategy is to reduce costs (Kokobu & Kitada 2010, 11).

Companies are not motivated to reduce the material loss generated if it requires too much of effort from them. Moreover, companies expect that some material loss is generated as a result of the input put into the system. If the material loss generated is within reasonable levels, companies assume that the expected profits can cover the loss. As Kokobu & Kitada (2010, 8) state companies are reluctant to reduce material losses in processes if the reduction of losses cannot be easily achieved. Moreover, the reduction of losses is ignored if the losses can be easily covered by the expected profits. This indicates that companies are willing to make material losses within acceptable limits. In this case, material losses are considered as an inevitable loss, which is not taken as a problem that should be fixed. (Kokubu & Kitada 2010, 8)

However, in the era of an economic slowdown the cost of waste may become important if the aim is to reduce production costs in order to remain competitive in the market. During recession, it is harder for companies to gain profits through sales because prices are needed to be reduced due to increased competition for customers. According to Pearce & Michael (2006, 202) recession increases competition between companies and as a consequence profit margins decline. In this case, the improvement suggestions in terms of the cost of waste could become important within a company since alternative management plans are needed to be considered in order to survive from the downturn (Kokobu & Kitada 2010, 18-19).

As a conclusion, it can be stated that firms are not willing to make reductions in material losses if the monetary value of the loss is not significant enough compared to company profit. Especially, the efforts towards reducing losses are not made if it requires heavy investments to obtain the savings. Companies are aware and comfortable with the fact that manufacturing processes generate material losses and thus, they do not consider it as a problem. Especially if the material losses are within accepted limits of the company, it is acceptable to make material loss. Rather it is important for companies to optimize material efficiency by increasing the product output generated from the processes in order to realize more revenue. However, the results suggested by MFCA may become desirable to realize in the event of an economic recession during which it can be hard to make enough profits through sale due to increased competition over customers between companies. In this case, it would become important to seek for profits through cost reductions such a realizing savings in the amount of waste generated.

7.2 Answers to the research questions

The main research question of this thesis was the following:

How can the material efficiency of the nesting process be improved?

The research question will be answered by responding to the sub-questions below.

RQ1: How does waste reduction in manufacturing processes contribute to material efficiency?

The theory states that material losses in production processes are hard to avoid. The most economically efficient method is to reduce the generation of scrap in the first place, which contributes to maintaining the primary value of material (Shahbazi et al. 2018, 24-25). As stated by Lilja (2009, 869) the outcome of improved material efficiency are financial savings in raw material purchases. In addition, increased material efficiency results in raw material savings (Flachenecker et al. 2017, 4-5). The findings of this research are in line with theory since the results show that material efficiency can be improved by reducing scrap in a production process, which results in both material and financial savings in raw material purchases. As a result, the hidden costs of waste are reduced which has a positive contribution to the profitability of the company.

RQ2: How do different sheet and plate sizes effect material efficiency in the nesting process?

The findings show that the size of the sheet or plate is an important factor in terms of increasing material efficiency in the nesting process. As stated by Kannan (2010) material utilization in nesting can be optimized by choosing the right sheet size. The findings of this research are in line with the theory since the use of different plate dimensions, in terms of width and length, results in different scrap rates in the nesting process. Thus, it is important to use the most optimal sheet and plate sizes in order to minimize the loss of material as well as financial losses.

RQ3: How can waste generation be measured in order to improve material efficiency?

This research applied KPI's that measure material efficiency in terms of scrap. The KPI's used were scrap generation and the cost of scrap. As stated by Shahbazi et al. (2018, 18) companies are mainly interested in performance indicators that measure financial results. Due to the high cost of input material, the cost of scrap is a popular KPI used to measure material efficiency in production processes (Shahbazi et al. 2018, 18).

MFCA was used as a tool in this study to identify the material flows of the nesting process and to calculate the physical and financial value of the scrap generated. The results show that MFCA can be effectively used to reveal the monetary value of waste by indicating how much material and material costs could be saved in a manufacturing process. As stated by Kokubu & Kitada (2015, 1280) MFCA aims to transform material flows transparent in order reveal physical and monetary losses, which can be used to support decision making and improve material management within a company.

RQ4: What is the difference in material efficiency measured in both physical and monetary terms between different metal plate size categories?

This research conducted a comparison between the following metal plate categories:

-width 1500mm versus width 2000mm
-width 2000mm versus 2070mm
-length 10000mm versus 11000mm
-length 12000mm versus 13500mm

In monetary terms, the results show small differences in the generation of scrap between the size categories when comparing the results against the case company's profit made in 2018. In general, the physical losses are bigger compared to the financial losses. The biggest difference in material efficiency is between the lengths of 10000mm and 11000mm from which the length of 10000mm shows greater material efficiency (5,26%). In the comparison between the widths of 1500mm and 2000mm, the width of 2000mm generates less scrap (2%). In the comparison between the lengths of 12000mm and 13500mm, the length of 12000mm shows greater material efficiency (0,88%). The smallest difference in material efficiency is between the widths of 2000mm and 2070mm from which the width of 2000mm is more efficient in terms of material use (0,34%).

RQ5: How much should the width of 1500mm cost in order to achieve the same costs in the total amount of waste (€) generated in the width of 2000mm?

The results show that the width of 1500mm generates more scrap compared to the width of 2000mm. In order to increase the material efficiency of the width of 1500mm, the current unit price (0,129€/kg) of the width should be decreased. The target unit price is calculated by dividing the monetary value of the scrap generated in the width of 2000mm with the physical amount of scrap generated in the width of 1500mm. The result shows that the unit price of the width of 1500mm should be 0,119€/kg in order to benefit from material efficiency if using the width of 1500mm instead of the width of 2000mm.

7.3 Managerial implications

The results show that the case company should use the plate width of 2000mm in its production instead of the width of 1500mm and 2070mm since the comparison shows that the scrap generation and cost of scrap are the lowest in the width of 2000mm. When it comes to the length comparison, the company should use the length of 10000mm instead of 11000mm whereas the length of 13500mm should be used instead of the length of 12000mm.

However, as mentioned before, the material cost savings gained through comparisons are not that significant when comparing the results against the case company's profit in 2018. In general, attention should be given to the cost of scrap generated, which is considerable compared to the case company's profit. Therefore, the case company should take actions towards decreasing the costs such as improving the nesting process or making investments in technical issues.

The case company should keep monitoring the generation of scrap and the cost of scrap in each size that are used in the case company's production. Only this way, the company can monitor the costs to stay within accepted limits in terms of scrap. Monitoring the scrap rates allows to detect inefficiencies in the production if the trend shows that scrap rates and costs start to grow unexpectedly. Especially, during economic recession, it is important to find costs that could be reduced in order to increase the profitability of a company. In this case, increasing material efficiency through cutting scrap levels would provide an easy way to contribute to the economic performance.

7.4 Validity and reliability of the study

The assessment of this research is based on evaluating the reliability and validity of this study. According to Golafshani (2003, 598) the reliability of a study refers to the degree to which the research results provide consistent results over time. In addition, the reliability relates to assessing whether the results represent the entire population of the study. Thirdly, the reliability refers to assessing whether the same results could be gained by using the same methods if the research was carried out again. (Golafshani 2003, 598) According to Kananen (2010, 131) the reliability of quantitative studies can be easily verified if the different stages of the research are well documented and justified.

Validity considers how well the research measures what it was supposed to measure (Golafshani 2003, 599). According to Kananen (2010) validity also measures the degree to which the research findings can be generalized. (Kananen 2010, 129). According to Tuomi (2007, 149) the overall reliability the study is also influenced by handling errors that might occur while entering data into a computer (Tuomi, 2007, 150).

The author aimed to increase the reliability of this study by documenting each step of this research as carefully as possible in order to increase the transparency of the research. However, this study involved lots of manual work in the data collection stage, which means that there is a possibility for errors having occurred while moving nesting details from reports to excel. However, the researcher aimed to be as careful as careful as possible while handling the data.

It was predetermined to select 30 sampling units for each subgroup. According to Vilkka (2007,57) the sample size should consist of at least 30 units if the aim is to compare different groups. Also, Tuomi (2007, 141) recommends that the sample size should consists of at least 30 samples in order to make statistical conclusions. Apart from two samples, this amount was fulfilled by most of the samples, which indicates that the amount of sampling units is adequate amount to generalize results within the case company.

However, it can be expected based on the dispersion measures that the average scrap % of each sheet and plate dimension can deviate to some extent. Since the beams are not manufactured as standard products, it might show a bit different average scrap % if new samples were drawn from the statistics for each dimension.

7.5 Suggestions for further research

Lastly, this section proposes suggestions for future research, which are derived from the limitations of this research. Since this research involved only the material efficiency of metal sheet and plates used in the beam production, the calculations could be extended to other products and other raw materials used by the case company. This could expose additional savings in material costs in other factories as well.

As mentioned in the limitations, this research does not measure the total material loss generated since remnants are not included in this study. Therefore, the future research could take into account remnants and scrap derived from remnants in order to obtain a more comprehensive picture concerning the amount of material loss generated per each plate and sheet size. This would provide a more complete view of the total scrap generated and whether there exist more possibilities for optimizing plate sizes.

Since this study was only limited to consider the direct material costs of material losses, the case company could also review the other hidden costs that occur from waste such as handling, storage and labour costs. The calculation of the hidden costs would help to reveal the true cost of waste. According to Doorasamy & Garbharran (2015, 74) the cost of waste is in total 10-30% of the total production costs of a company. Thus, taking into account each hidden cost of waste would reveal the cost that could be saved by reducing the amount of scrap.

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