USING BWM AND ELECTRE III TO AID MANUFACTURING UNIT PROCESS OPTIMIZATION IN HEALTHCARE TECHNOLOGY INDUSTRY

Master Thesis

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PHILIPS

Using BWM and ELECTRE III to aid manufacturing unit process optimization in Healthcare Technology industry

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PREFACE AND ACKNOWLEDGEMENTS

This Master Thesis to me represents much more than a research paper written for a course at University. It is a representation of a number of new beginnings, an accumulation of new learnings and just one end, that of my higher education.

The past two years that I spent completing the Management of Technology study have played a major role in my life. While pursuing this degree I have truly found direction and got the opportunity to explore and further develop all my capabilities to the full extent.

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EXECUTIVE SUMMARY

The integration of technology across all industries has brought up the need for companies everywhere to be more adaptive in order to gain and maintain competitive advantage and this trend did not skip the healthcare industry either. One way companies tackle this is by means of implementing different ways of process optimization in their supply chains, which is why there exists a large body of research addressing the choices involved with specific means of process optimization. However, a research gap exists when it comes to the decision-making process of choosing a focus area for process optimization in healthcare technology supply chains, and more specifically within the manufacturing units of the companies involved. This thesis presents a new multi-criteria decision-making (MCDM) approach for healthcare technology companies that wish to take the first step in process optimization of their manufacturing units namely finding a focus area to implement it in.

In order to contribute to the existing research and offer a solution for companies facing this issue, the main objective of this thesis is designing a framework which can be used for companies in the field of healthcare technology like Philips who wish to optimize (parts of) their manufacturing processes, but do not have a clear idea on how to approach this issue, due to its complexity. The objective is achieved by answering the following main research question: "In what way can a healthcare technology company determine a focus area for process optimization within their manufacturing unit?" Subsequently, 6 sub-questions are posed in order to answer the main one.

The first step in answering the research question was conducting a literature review in order to identify the nature of the problem and the fitting MCDM methods around which the framework is centered. The methodology consists of three main methods namely Semi-structured interviews, Best Worst Method (BWM) and ELECTRE III. Once the methods were chosen, the framework was applied to a real case in a manufacturing unit of Philips, an innovative company in the field of healthcare technology. A thorough research into the company structure as well as its organization structure was done in order to find the relevant scope of the research. The final chosen scope was the assembly process of the Azurion Floor IGT System Stand, where the 8 assembly process steps represent the alternatives to be ranked within the MCDM analysis. In order of assembly, the steps are Preparation, Mounting 1, Cabling 1, Mounting 2, Adjustment, Cabling 2, Testing and Mounting 3.

Performing stakeholder mapping and utilizing the power/interest grid made it possible to select six relevant decision-makers with different roles to be included in the data collection for BWM and ELECTRE III. The stakeholder map helped identify 3 main branches within Philips relevant to the chosen scope namely Manufacturing, IGT Systems R&D and Quality Assessment, so it was concluded that stakeholders from all the branches need to be involved in the decision-making process in order to ensure that the results are representative of the preferences of the whole company. The chosen decision-makers were found to be located in the top-right quadrant of the power/interest grid meaning that they possess the highest levels of both power and interest in the particular situation and these were R&D Designer, Development Engineer, Manufacturing Engineer, Product Industrialization Engineer, Production Improvement Manager and QA Engineer. These decision-makers were then interviewed in two rounds by making use of semi-structured interviews in order to formulate the set of three main relevant criteria (Flexibility, Requirements and Technology) which are described with a total of seven criteria for the analysis (R&D Flexibility, Manufacturing Flexibility, Complexity, Number of workers required for step completion, Area needed for step completion, Time required for step completion and Connection to future systems and backwards compatibility), as well as to provide other necessary data.

The MCDM analysis yielded the weights of the criteria, and finally the ranking of the assembly process steps. According to BWM results based on the data provided by the decision-makers, the highest weighing criteria was Complexity, closely followed by Connection to future systems and backwards compatibility. Based on the weights and preference, indifference and veto thresholds assigned by the decision-makers, ELECTRE III ranked the process step Cabling 2 as the first one for process optimization, meaning that it was assigned the highest score among all the alternatives. This result is considered reasonable, as the Cabling 2 step had performed very well with respect to almost all criteria. Based on the results, the main recommendation given to the company was to perform the implementation of process optimization within the Cabling 2 step. Furthermore, the company was advised to conduct another MCDM analysis in order to determine the best way of process optimization for the Cabling 2 step.

Finally, the theoretical and practical contributions of the thesis research are addressed together with its limitations and opportunities for future research. Most notably, possible cognitive and motivational biases were addressed, as well as what was done to mitigate them. The thesis ends with a summary of the main conclusions and an overall reflection.

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1. INTRODUCTION

1.1. Background

In the present time, companies all over the world that need to perform any form of operational management as part of their business and are involved in some parts of a supply chain are working hard on increasing the overall efficiency of their processes. This is done for a number of reasons, some of which are cost minimization, fulfillment of sustainability goals, expansion, better adaptability to all kinds of changes and so on (Lichocik & Sadowski, 2013). In order to remain competitive, companies need to continuously improve in all spheres, as being able to adapt quickly to the current, fast-paced environment is becoming an increasingly important source of competitive advantage. One thing that significantly slows down this process is the fact that, most of the time, there are several decision makers involved, who often have different sets of preferences, making coming to an agreement increasingly difficult. Furthermore, there exist a variety of factors, both direct and indirect, and quantitative and qualitative, specific to each case, that dictate the way a problem in question can be solved (Wu et al., 2019). This means that some form of guidance is needed to make the decision-making process for these companies more efficient and less tedious. In order to ease this process and achieve the wanted efficiency, companies with manufacturing units are asking managers for help with designing suitable frameworks and implementing certain strategies for this purpose.

One of the industries that requires constant adaptability from the businesses involved is healthcare. Throughout time, technologies have had a significant effect on the way health, care, and disease are perceived (Vandemeulebroucke et al., 2022). Healthcare settings are constantly experiencing technological advancements in all areas, with the aim of preventing, managing, or resolving health-related issues and enhancing the overall quality of life for individuals (World Health Organization, 2019). This trend has been amplified in recent times and is expected to persist in the coming years (Flear et al., 2013). Companies that are involved in healthcare technology development face a variety of complex issues within healthcare supply chains and are under constant pressure to drive the costs down while maintaining the output of innovation.

One thing that is frequently overlooked when it comes to process optimization within manufacturing units is the beginning of the process. Namely, there is a large volume of research present with respect to tackling specific issues within supply chains and manufacturing units, such as supplier selection, location selection, technology selection and so on. What is missing is an approach that can be used for choosing a focus area where optimization will be implemented. This is an important and often difficult step for companies with large portfolios of different products and processes and diverse departments involving decision makers with largely different priorities, interests, and preferences. Naturally, it is very challenging to maintain innovative capacity and adaptability to changes if there is no clarity on which problem should be addressed first.

Philips is considered as one of the leaders in healthcare technology, being involved in research, design, development and engineering, manufacturing, servicing, and commercialization of personal healthcare devices, as well as medical systems and devices made for hospitals and other patient care facilities (Spekowius & Wendler, 2006). The size of the company, vast variety of products and processes present, and a large number of stakeholders with different viewpoints all contribute to the complexity of supply chain optimization within this company and the others alike. More specifically, optimizing the processes within manufacturing units of such a company can be rather difficult, as it seeks involvement and alignment of decision makers with many different roles, academic backgrounds and responsibility areas. In order to generate recommendations for making improvements within the manufacturing unit in question, the preferences of all the relevant stakeholders need to be collected and evaluated.

A Multi-criteria Decision-making (MCDM) problem is defined as a problem where the decision maker or more of them, choose a solution by picking the best alternative based on certain criteria (Majumder, 2015). Many problems that occur in the field of supply chain management can be regarded as MCDM problems, because of the involvement of various decision-makers, as well as the different factors (criteria) which need to be taken into account when choosing the best solution out of presented alternatives (Raut et al., 2017). The variety of decision-makers with different viewpoints located within different departments of the company makes this problem a group decision-making problem. Thus, the complexity is even greater.

One of the main ideas of this thesis is that MCDM methods can be useful in developing manufacturing unit optimization frameworks for companies involved with healthcare technologies, by means of delineating the criteria that are relevant for them, as well as ranking the alternative solutions. Even though each specific case is different and with it the criteria as well, it is still useful to have a stepwise framework applied to a real-case scenario as a guide.

1.2. Research objective and research questions

The main objective of this research is to design a framework which can be used for companies in the field of healthcare technology like Philips who wish to optimize (parts of) their manufacturing processes, but do not have a clear idea on how to approach this issue, due to its complexity.

The main research question that stems from the research objective is:

In what way can a healthcare technology company determine a focus area for process optimization within their manufacturing unit?

In order to successfully answer the main research question, a number of steps need to be taken, so several sub-questions are defined accordingly.

First, it is necessary to define the processes that are present in the manufacturing unit. Once this overview is complete, it is possible to identify the alternatives that will later be ranked.

1. *Which processes within the manufacturing unit are considered as the possible focus areas?*

To make sure that the preferences of the company are representative and reliable, all the decision makers need to be carefully selected.

2. *Who are the relevant decision makers within the company?*

After it is clear who the decision makers are, it is necessary to collect data on the criteria that are relevant for the issue that is being addressed. Furthermore, the importance of the criteria plays a great role as it is what ultimately determines the final ranking of the alternatives.

3. *What are the relevant criteria for a company in choosing a focus area for process optimization within a manufacturing unit?*
4. *What is the importance (the weights) of these criteria?*

Once the weights of the are computed, the ranking of the alternatives needs to be performed, so that recommendations for the company can be formulated accordingly.

5. *What is the ranking of the focus areas?*
6. *Which recommendations and strategies can be derived from the analysis?*

1.3. Research design

This section outlines the steps that will be taken in order to successfully carry out the research and answer the research questions stated in Section 1.2.

The research can be divided into 4 phases namely Research Phase, Data Collection Phase, Data Analysis Phase and Results discussion and recommendations. A schematic representation of the research phases and how each of the steps is connected to answering the research questions can be seen in Figure 1 below.

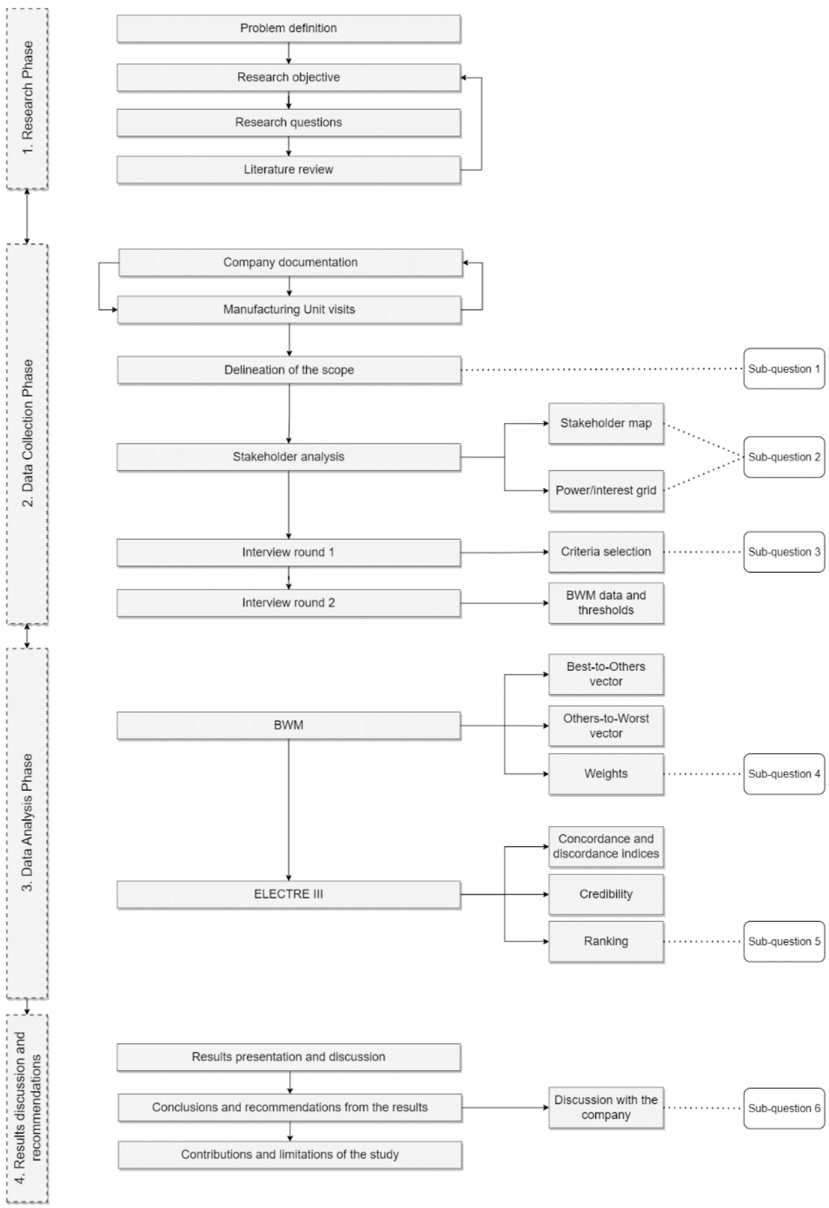

Figure 1: Scheme of the research design

The first phase began with a problem definition, followed by the first versions of the research objective and research questions. Then, an elaborate literature review in the field of supply chain management was conducted in order to identify the research gap. The literature study begins broadly, by first assessing the available literature in the field of process optimization within supply chains. Then it moves on to explore the role of MCDM in healthcare supply chain management, followed by a review of the most frequently used MCDM methods and their applications in specific problems regarding manufacturing units, narrowing down towards the Best-Worst Method and ELECTRE. The known versions of these two MCDM methods are then researched, eventually filtering out Linear BWM and ELECTRE III which are used in the thesis. At this point, the research objective and research questions are revisited and redefined. Finally, a literature review regarding the relevant criteria in this field was conducted, followed by the literature discussing Group-decision making.

The second phase starts in parallel to the literature review and here information about the manufacturing processes within the manufacturing unit of the company was collected from the documentation provided by the company, as well as through daily on-site visits to the manufacturing unit. This information made it possible to gain an overview of all the products and processes that are present in order to determine the scope of the research. Furthermore, the time at the company in the beginning was also used to understand the company structure and gain an insight into who the involved stakeholders are.

Once a broad overview of the stakeholders is obtained, it is possible to construct a Stakeholder map, select the relevant stakeholders and make use of a Power/Interest grid in order to determine who are the decision-makers that should be involved in the MCDM analysis. The outcome of this analysis is a list of the relevant decision-makers that will be interviewed as part of the BWM and ELECTRE III analyses, and whose collective preferences will ultimately represent the preferences of the company.

In total, 2 rounds of interviews were conducted. Aside from the literature review, interviews are a key component in determining the criteria relevant for the study, so the goal of the first round of interviews was to arrive at a fixed set of criteria that will be used in the analysis. The second round of interviews had the purpose of collecting the data about the preferences of the decision-makers that is needed in order to perform the MCDM analyses. More precisely, the data necessary to form the Best-to-others ad Others-to-worst vectors for BWM was collected, as well as the values of the preference, indifference and veto thresholds for ELECTRE III. Both rounds of interviews were done in a group setting with the 6 chosen decision-makers, by making use of semi-structured interviews (Kallio et al., 2016). The decision-makers were asked to come to a consensus regarding their preferences and provide a single answer.

Then, the data from the BWM interviews was analyzed through a number of computational steps carried out by the BWM Solver, which will yield the weights of the relevant criteria (BWM Solvers | Best Worst Method, n.d.). Then, ELECTRE III was used as a ranking method for the alternatives.

These results were then presented and discussed, together with the possible biases, setbacks, and downsides. Finally, the results were used for formulating recommendations and strategies for the company regarding which focus area they should choose for process optimization.

2. LITERATURE REVIEW

2.1. Healthcare technology supply chain management and MCDM

This sub-section will address the literature on the current trends in the healthcare industry, and more specifically healthcare technology and the relationship of the trends with healthcare supply chains, so that it could be explored whether supply chain management plays a significant role in healthcare technology. Finally, the role of MCDM in healthcare technology supply chain management is discussed.

Mathew and John (2013) point to the healthcare industry experiencing a significant increase in prices for almost all of its products and services. This rapid and concerning trend is mainly attributed to the supply chain, which is considered a major cost driver and thus has become a primary focus for industry stakeholders. Pinna et al. (2015) also address the raising costs and point out supply chain innovation as being one of the key research topics of the future within the industry, due to various factors, both quantitative and qualitative in nature (e.g. political and economic) which are influencing healthcare systems worldwide and need to be addressed and taken into account. Dixit et al. (2019) have conducted a thorough literature review of 143 papers in the field of healthcare supply chain and have concluded that future research into methods for increasing supply chain efficiency is necessary.

AbuKhousa et al. (2014) wrote about the need for tools that will help with decision-making processes within healthcare supply chains and have proposed a simulation and modeling (SM) approach to aid this. The fact that some decision-making problems have already been identified in this sector implies that MCDM methods could indeed be useful in this context.

Multi-Criteria Decision Making (MCDM) pertains to the organization and resolution of decision-making and planning issues that encompass diverse criteria (Majumder, 2015). In the research paper written by Hien and Thanh (2022), two MCDM methods are used as a tool to aid the process of selection and evaluation of suppliers of vaccines within the medical sector. The need for this process to be carried out with great care stems from certain storage standards that were set and need to be fulfilled, in order to minimize waste and not to endanger human lives. This is a good example of how MCDM can be used to address supply chain issues and ease the process of complying with the set standards in the medical field.

Pamucar et al. (2022) highlight the role of Multi-Criteria Decision Making (MCDM) in healthcare supply chains (HSCs). They emphasize that supplier selection is a critical decision-making problem in HSCs, especially throughout the COVID-19 pandemic when there was a high demand for a variety of medical products. By applying MCDM, healthcare centers can evaluate and compare suppliers based on their performance over different decision criteria, considering the complex and uncertain nature of the pandemic. The paper combines two MCDM methods, specifically the Measuring Attractiveness by a Categorical Based Evaluation Technique (MACBETH) for determining the weights of the criteria and the Combinative Distance-based Assessment (CODAS) method to evaluate and rank the alternatives, with respect to supplier selection issues in HSCs throughout the pandemic of COVID-19. The authors claim that, by utilizing such methods, healthcare managers can make more reliable and accurate decisions, ensuring the availability of critical medical products and supporting the overall resilience and sustainability of the healthcare supply chain.

Singh and Parida (2022) wrote a review discussing disruptions occurring in healthcare supply chains. The review identifies existing modeling approaches such as Robust Optimization, Simulation and Game Theory, but suggests that more progress is needed. They address MCDM as a potentially useful approach for achieving more stability and minimizing risks within HSCs. Finally, the authors state that the research field is expected to grow and that MCDM is to play an increasingly important role both the academic field, but also for practitioners when it comes to maintaining/increasing competitiveness in the healthcare sector.

What the mentioned papers have in common is that they highlight the effectiveness of MCDM methods in addressing various challenges in healthcare supply chain management, such as supplier selection, performance evaluation, network design, and decision-making under uncertainty.

2.2. MCDM Methods

This sub-section gives an overview of the existing literature on different MCDM methods and brief descriptions including strengths and weaknesses of the most widely used methods.

MCDM methods are classified in two groups, namely compensatory and non-compensatory (outranking) methods (Majumder, 2015). Compensatory methods in decision-making involve systematically evaluating alternatives based on multiple criteria. Here, positive attributes of an alternative can compensate for negative attributes, allowing for trade-offs between different criteria. In contrast, outranking methods take a different approach and aim to eliminate dominated alternatives, by focusing on comparing alternatives based on individual criteria (Mulliner et al., 2016). Dominance within the outranking framework considers the importance of criteria through the use of weights. An option outranks another if it performs better on enough criteria of sufficient importance and is not significantly inferior on any single criterion. The assessment of options is based on their extent of outranking against a set of threshold parameters. Outranking methods allow for the possibility of incomparability between options, which is different from indifference and can occur due to missing information. However, critics highlight the arbitrary definitions of outranking and the manipulation of threshold parameters by decision makers (Majumder, 2015). Some of the most frequently utilized compensatory MCDM methods include Multi Attribute Utility Theory (MAUT), Analytic Hierarchy Process (AHP), TOPSIS, whereas the most used non-compensatory methods are ELECTRE and PROMETHEE (Mulliner et al., 2016).

In order to identify the existing MCDM methods, literature reviews on this topic were found and the three that were taken into account were the ones written by Wątróbski et al. (2019), Ceballos et al. (2016) and Velasquez and Hester (2013). The literature mentions 49 MCDM methods that are present and can be used for solving (complex) MCDM issues. The methods that were deemed as some of the most used were Multi Attribute Utility Theory (MAUT), Analytic Hierarchy Process (AHP), Analytic Network Process (ANP) and Case-based Reasoning (CBR) (Velasquez & Hester, 2013).

MAUT was formulated as an extension to the Multi Attribute Value Theory formulated by Fishburn and Keeney (1974) and its main distinction from other methods lies in the possibility of including uncertainty and risk into the MCDM process. In comparison to MAVT, MAUT is considered as more rigorous (Velasquez & Hester, 2013). This method is regarded as the most used and applied MCDM method, according to Velasquez and Hester (2013). The main disadvantage of both MAVT and MAUT is that they employ iterative and intricate methods for estimating utility, which are considered to be unreliable. Furthermore, these methods rely on hypothetical lotteries and fail to capture the interaction between alternatives within a criterion and across multiple criteria (Dhurkari, 2022).

AHP was first introduced by Saaty (1977, 1980) and it is mainly used for finding solutions for problems set in a multi-variate environment, by yielding different weights for the available alternatives (Bernasconi et al., 2010), where the highest weight marks the best alternative. The main concept underlying this method is the measurement of the criteria on a ratio scale ranging between 1 and 9 (Saaty, 1977).

Although AHP has been previously criticized regarding it not being compliant with the axioms of the classic utility theory (Dyer, 1990), this method is still very much used within MCDM, due to its ease of use and scalability. ANP is a non-linear and a more general form of AHP and has been mostly used in combination with other MCDM methods (Saaty, 2006; Velasquez & Hester, 2013). AHP fails to consider the interaction across criteria as well as between alternatives within a criterion. While ANP does capture both of those interactions, its downside is that it is prone to biases by the decision-makers (Dhurkari, 2022).

TOPSIS method aims to identify the alternative that is closest to the ideal solution and furthest from the negative ideal solution. It offers several advantages, including a straightforward process, ease of use, and programmability. Regardless of the number of attributes, the number of steps remains constant (İç, 2012). However, a drawback of TOPSIS is that it utilizes Euclidean Distance, which overlooks attribute correlations. Weighing attributes and maintaining judgment consistency, particularly with additional attributes, can be challenging (Velasquez & Hester, 2013).

One method that was not included in the assessed literature reviews due to its novelty is the Best Worst Method (BWM). This method was introduced by Rezaei (2015). Within BWM, the relevant decision makers are asked to define the "best" and "worst" criteria from the set, after which all the other criteria are compared with respect to the "best" and "worst" ones. This is followed by obtaining the weights of the criteria by making use of pairwise comparison (Rezaei, 2015). The main advantage of this method is better reliability due to a better consistency ratio that stems from the smaller number of pairwise comparisons needed to be done (Rezaei, 2015).

ELECTRE is an outranking method that is often applied to all kinds of supply chain decision-making issues (Uysal, 2014). It makes use of concordance analysis and its main advantage over other methods is that it takes into account uncertainty (Velasquez & Hester, 2013). ELECTRE II made by Roy and Bertier (1973) and ELECTRE III made by Roy (1978) are other versions of ELECTRE which are also frequently used in MCDM literature (Sevkli, 2010).

PROMETHEE is also an outranking method with several versions. PROMETHEE I and PROMETHEE II were introduced by Brans (1982). Both make use of computing a positive and a negative outranking flow and PROMETHEE I yields a partial ranking, while PROMETHEE II results in a full ranking, which is normally desired by the decision-makers (Behzadian et al., 2010). Later, PROMETHEE III for interval-based ranking, PROMETHEE IV for continuous sets of solutions, PROMETHEE V for when there are segmentation constraints and PROMETHEE VI for the human brain representation were introduced (Velasquez & Hester, 2013). The main advantage of this method is its ease of use, as well as the fact that it does not rely on the assumption that the criteria are proportionate, allowing for greater flexibility (Brans et al., 1986). A literature review conducted by Behzadian et al. (2010) identified 195 research papers in which PROMETHEE methods were applied and has divided them according to nine areas: "Environment Management, Hydrology and Water Management, Business and Financial Management, Chemistry, Logistics and Transportation, Manufacturing and Assembly, Energy Management, Social, and Other Topics", proving that this method is widely used. However, there are some disadvantages in that it lacks a clear and systematic approach for assigning weights to the criteria, making the weight assignment process subjective and potentially inconsistent. Furthermore, while the method requires the assignment of values, it does not provide a clear guidance or methodology for determining these values, leading to potential ambiguity and challenges in the decision-making process (Velasques & Hester, 2013).

A comparative study on the use of PROMETHEE and ELECTRE was done by Majdi (2013) and it deemed ELECTRE III as a better choice in the context of sustainability assessment purposes for several reasons.

First, the author states that ELECTRE III offers more comprehensive features compared to PROMETHEE, providing clear and meaningful results despite its complexity for users. This enables the ranking and selection of companies based on a higher concordance index, allowing decision-makers to identify better resource recovery options and explore opportunities for enhancing sustainability through resource integration. Additionally, ELECTRE III employs a unique procedure that involves both ascending and descending ranking for each pre-order, whereas PROMETHEE relies solely on descending distillation for ranking. Finally, the incorporation of veto thresholds in ELECTRE III decreases the extent of compensation between criteria, resulting in significantly different rankings in comparison to the ones obtained from PROMETHEE.

Banihabib et al. (2017) compared compensatory methods Additive Weighting (SAW) and Analytical Hierarchy Process (AHP) to the non-compensatory ELECTRE III method in the case of ranking strategies for water resources strategic planning, based on six relevant criteria. Although all three methods ranked water transfer strategy the lowest, the sensitivity analysis of the methods revealed that ELECTRE III exhibited lower sensitivity compared to SAW and AHP, particularly for changes in the two most significant criteria weights. This finding demonstrates the advantage of ELECTRE III, in that it considers the fuzzy nature of decision makers' preferences by incorporating thresholds. Consequently, the results obtained from ELECTRE III are considered more reliable and suitable for decision makers in promoting sustainable development in the region.

2.3. MCDM in manufacturing unit problems

This sub-section encompasses the relevant literature on applications of different MCDM methods to problems regarding manufacturing units within companies.

A very common MCDM problem of location selection for a new manufacturing unit was addressed by Canbolat et al. (2007) and the proposed solution was acquired by combining MAUT and a decision tree. Kirkwood (1982) applied MAUT method to solve another location selection problem, this time for a nuclear power plant. MAUT was also used by Kailiponi (2010) for the problem of making decisions about evacuations, which was normally being done by emergency managers. AHP method has been utilized for solving problems of selecting a location for a manufacturing plant (Chang & Lin, 2015). Furthermore, Mousavi et al. (2013), have presented a combination of AHP and PROMETHEE for criteria assessment and alternative ranking. Görener et al. (2012) have used AHP in combination with another prominent management tool, the SWOT analysis, in order to assess the different SWOT factors. Görener (2012) has also written a paper on combining SWOT with both AHP and ANP in order to increase the reliability of the results. Due to its nature, applications of CBR for manufacturing unit issues were not discussed in literature, but only for applications such as vehicle insurance (Daengdej et al., 1999). Athawale and Chakraborty (2010) have applied PROMETHEE II method for a problem regarding selection of a facility layout. The Best Worst Method was applied by Kheybari et al. (2019) for renewable energy facility location selection. It was also used for solving other supply chain issues, such as forecasting customer churn, addressed by Duchemin and Matheus (2021), coffee supplier selection (Rahmawati & Salimi, 2022) and selection of partners for environmental management (Govindan et al., 2019). The conclusions from these papers point to BWM being a useful method for this type of issues.

2.4. BWM

Best Worst Method (BWM) was first introduced by Rezaei (2015) as a new MCDM method, with a nonlinear minimax model, which meant that sometimes the method would yield multiple optimal solutions. Although this is sometimes desirable, in order to make it possible to obtain only one optimal solution, a linear BWM model was introduced later by Rezaei (2016). Other variants of BWM include Best-Worst Tradeoff Method (BWT), which is meant to take into account the ranges of the attributes used in the pairwise comparisons (Liang et al., 2022a). Nonadditive BWM is used in cases when interactions between the criteria are present and need to be addressed by the MCDM method. This is made possible by incorporating the Choquet integral into the computational steps (Liang et al., 2022b). Finally, Bayesian BWM is used when the MCDM problem is a group decision-making problem, namely when there are multiple decision-makers involved, and they have different preferences. It presents a way to aggregate the weights of the decision-makers, so that the final weights of the criteria can be found (Mohammadi & Rezaei, 2020).

There are several advantages of BWM in comparison to other MCDM methods. The process of collecting the necessary data for the analysis is characterized by its simplicity, allowing for easy communication with decision-makers without them requiring extensive knowledge of MCDM. This feature enhances the accessibility of the method. Additionally, BWM is anticipated to mitigate the likelihood of biases such as anchoring bias (Rezaei et al., 2022a) and equalizing bias (Rezaei et al., 2022b), thereby assuring a more accurate and unbiased decision-making processes.

2.5. ELECTRE

When the first version of ELECTRE was introduced as ELECTRE I, it was the first MCDM method that involved outranking relations (Roy, 1968). Nowadays, there are many different versions on top of EECTRE I, such as ELECTRE II, III, IV and TRI (Yu et al., 2018). Even though all versions are based upon the same core concepts, there are variations according to different kinds of decision-making issues. ELECTRE I is used for choice problems, ELECTRE II, III and IV for ranking problems, and ELECTRE-TRI for sorting problems (Marzouk, 2011). Due to the nature of the problem this Thesis is addressing, aside from ELECTRE I which is the foundation for all other ELECTRE methods, only ELECTRE versions that address ranking problems are discussed in more detail in the following text.

ELECTRE I, introduced by Bernard Roy (1968), is the foundational version of the ELECTRE method. It employs a pairwise comparison approach to rank alternatives based on outranking relations among criteria. ELECTRE I uses concordance and discordance thresholds to determine the strength of relationships between alternatives and criteria. Alternatives that meet the concordance threshold and do not violate the discordance threshold are considered as outranking others.

ELECTRE II formulated by Roy and Bertier (1973) builds upon the ELECTRE I and introduces additional refinements. It incorporates veto thresholds, which allow decision-makers to establish conditions for strong preferences or vetoes on certain criteria. These are preference, indifference and veto thresholds for the values of the alternatives with respect to the chosen criteria. Above the preference threshold (p), the decision-maker shows a clear preference for one alternative, below the indifference threshold (q), he/she expresses indifference between two alternatives, whereas the veto threshold (v) is the value above which the decision-maker is willing to negate all other outranking relationships with respect to the rest of the criteria (Rogers and Bruen, 1998).Furthermore, this version allows decision-makers to express more specific preferences and introduces the concept of outranking indices (Figueira et al., 2005).

ELECTRE III, developed by Roy (1978), further enhances the ELECTRE method by introducing a concordance index and a discordance index. These indices provide a more detailed analysis of the outranking relationships among alternatives, and they make it possible to obtain a ranking even with inaccurate data (Roy, 1991). ELECTRE III incorporates weights for criteria and thresholds for concordance and discordance, allowing decision-makers to express their preferences more precisely. The development of ELECTRE III meant that ELECTRE II method was now replaced (Roy, 1991). The main advantage of ELECTRE III in comparison to other methods is that it is able to deal with uncertain and inaccurate data.

2.6. Relevant criteria

A thorough literature research was done in order to identify the criteria that was previously used in problems similar to the one addressed in this thesis. Namely, the focus was on scientific literature in the fields of healthcare technology supply chains, manufacturing unit problems and general supply chain problems. These criteria will be used as a starting point in defining a final list of criteria that will be applied to a real case within Philips.

The criteria found in literature and the respective sources are presented in Table 1 below. Due to the complexity of the problem and the variety of influencing factors, it was deemed necessary to group the criteria into clusters, which are then divided into criteria that further branch out to sub-criteria. This way of grouping was done according to the paper written by Alimardani et al. (2013).

Criteria Cluster	**Criteria**	**Sub-criteria**	**Sources**
Performance	Time	Transportation time	Wu et al. (2009), Ghaleb et al. (2020)
		Distribution time	Wu et al. (2009), Ghaleb et al. (2020)
		On-time response to request	Sari et al. (2008); Büyüközkan & Cifci (2011)
		Delivery time	Sari et al. (2008); Büyüközkan & Cifci (2011), Ghaleb et al. (2020)
	Progress	Customer satisfaction	Alimardani et al. (2013)
		Customer-driven innovations	Sharifi & Zhang (1999)
	Quality	Information quality	Büyüközkan & Cifci (2011)
		Product quality	Luo et al. (2009), Wu et al. (2009), Ghaleb et al. (2020)
		Service level	Luo et al. (2009), Wu et al. (2009)
Cost	Caution cost		Sari et al. (2008)
	Operating expenditure	Support system cost	Tam & Tummala (2001), Ghaleb et al. (2020)
		Maintenance cost	Tam & Tummala (2001), Ghaleb et al. (2020)
		Production cost	Wu et al. (2009), Ghaleb et al. (2020)
	Capital expenditure		Tam & Tummala (2001); Wu et al. (2009)
Flexibility	Manufacture flexibility		Tsourveloudis & Valavanis (2002); Lin et al. (2006), Ghaleb et al. (2020)
	Establishment flexibility		Wu et al. (2009), Ghaleb et al. (2020)

Criteria Cluster	Criteria	Sub-criteria	Sources
	Multi-skilled and flexible people	Employee skills utilization	Ghaleb et al. (2020)
		Continuous training and development	Tsourveloudis & Valavanis (2002), Ghaleb et al. (2020)
	Product volume flexibility		Tsourveloudis & Valavanis (2002), Ghaleb et al. (2020)
	Product flexibility		Sharifi & Zhang (1999), Ghaleb et al. (2020)
	Complexity		Ghaleb et al. (2020)
Technology	Future technology development		Sharifi & Zhang (1999); Tam, Tummala (2001)
	Interoperability with other systems		Tam & Tummala (2001); Tsourveloudis & Valavanis (2002)
	Compliance with international standards		Tam & Tummala (2001); Lin et al. (2006)
	System redundancy		Tam & Tummala (2001)
	System reliability/availability		Tam & Tummala (2001); Lin et al. (2006)
	Technical features/characteristics		Sharifi & Zhang (1999); Büyüközkan & Cifci (2011)

Table 1: Relevant criteria from literature

2.7. Group decision-making in MCDM

Group decision-making in the context of multi-criteria decision-making (MCDM) refers to the process of multiple actors making decisions depending on multiple criteria or factors that influence the outcome. It involves a collective effort where a group of individuals with diverse perspectives, knowledge, and/or expertise come together to reach a consensus or make a joint decision that incorporates different criteria (Hirokawa & Poole, 1996).

The group decision-making process aims to integrate the preferences and judgments of individual group members to arrive at a final decision that takes into account the collective wisdom and expertise of the group. Group decision-making in MCDM offers several advantages. It enables the utilization of diverse knowledge and perspectives, enhances the quality of decision outcomes, and fosters better understanding and acceptance of the decision among the stakeholders. However, it also introduces challenges such as information overload, conflicts of interest, and difficulties in reaching consensus.

Several approaches and methods have been proposed to facilitate group decision-making in MCDM. These include analytic hierarchy process (AHP) (Saaty, 1980), technique for order preference by similarity to ideal solution (TOPSIS) (Wang & Elhag, 2006), fuzzy sets theory (Zadeh, 1965), and multi-objective optimization techniques (Boix-Cots et al., 2023), among others. These approaches provide frameworks and algorithms to aggregate individual preferences, resolve conflicts, and ultimately support the group in reaching a collective decision.

Research in the field of group decision-making in MCDM has explored various aspects such as group dynamics, preference elicitation techniques, consensus measurement, and decision support systems with the aim of improving the effectiveness and efficiency of group decision-making processes, enhancing the understanding of group dynamics, and develop methodologies that can effectively handle complex decision problems (Bose et al., 1997; Morente-Molinera et al., 2015; Tanino, 1988)

Belton and Pictet (1997) suggest that there are three ways in which it is possible to deal with different views of decision-makers, namely sharing, aggregating, and comparing. Sharing refers to the pursuit of a common element through consensus, facilitated by deliberative discussions and negotiation. By addressing and explicitly discussing the underlying causes of differences, sharing aims to reduce them and foster agreement among participants. Aggregating entails seeking a common element through compromise, often achieved via voting or the calculation of a representative value. While acknowledging the presence of differences, aggregating focuses on minimizing them without delving into explicit discussions of their causes. When comparing various perspectives or viewpoints, the objective is to obtain individual elements and potentially reach a consensus by negotiating independent results. Comparing recognizes and acknowledges the existence of differences, without necessarily aiming to actively diminish them. The choice between the three methods depends on the context of the MCDM issue.

The method that is used in this research is sharing, as it is said to ensure a shared understanding, by means of dealing with possible different interpretations from the decision-makers from the beginning, whereas these differences might be completely overlooked in aggregating and only recognized in later stages when using comparing, as these two ways encourage individual evaluations (Belton & Pictet, 1997).

2.8. Main takeaways from the literature review

The literature review was initiated broadly, investigating the current trends in healthcare technology and healthcare supply chains, as well as the role of MCDM in solving issues brought on by those trends. The main findings point to different MCDM methods serving as a valuable tool in healthcare supply chain management. After these findings, the next step was to review existing MCDM methods by addressing their strengths and weaknesses and applicability to the case addressed by this study, eventually narrowing down to the methodology that will be used. This thorough review resulted in the choice of a combination of Linear BWM and ELECTRE III as a new decision-making approach for several reasons. First, non-compensatory MCDM methods have been characterized as more reliable in comparison to compensatory ones by the literature. Among non-compensatory (outranking) methods, ELECTRE is deemed as the best, and has been applied to many supply chain management issues successfully. Linear BWM yields weights that are compatible with ELECTRE III, which cannot be said for many other methods. Furthermore, research describing the application of Linear BWM, as well as the combination of BWM and ELECTRE III seems to be lacking. Following this step, a brief literature review was conducted in order to confirm the use of different MCDM methods in manufacturing unit issues, and this was done successfully. Afterwards, the different versions of ELECTRE and BWM were discussed and explained. Finally, a deep-dive review was conducted into the relevant criteria for the research topic. These criteria serve as a starting point for choosing the set of criteria that will then be used in the case of Philips. Lastly, theory behind group decision-making is discussed, addressing different ways of group decision-making, namely sharing, aggregating and comparing. The chosen method for mak8ing a decision is sharing, as it takes into account the differences in opinions of the decision-makers from the very beginning of the analysis.

Based on the findings from the literature, it can be concluded that there indeed exists a research gap when it comes to using MCDM methods for finding a focus area for process optimization within manufacturing units of healthcare technology related companies. The literature on the application of MCDM methods for manufacturing unit problems mostly focuses on finding solutions for specific problems once the focus area has already been determined. However, there is no clear pathway defined for the step that comes before, namely deciding what to focus on. Furthermore, making use of the BWM method in such a problem presents another opportunity for scientific contribution, as it is a novel MCDM method that still hasn't been frequently applied in research. On the other hand, ELECTRE III has been proven to work by numerous research papers concerning MCDM in supply chain management and its non-compensatory nature also represents an advantage in comparison to other methods found in literature. Scientific novelty also applies to the use of the combination of BWM and ELECTRE III, which is one of the main reasons for choosing to use the combination of these methods for the analysis. Additionally, the weights that stem from BWM can be considered as intrinsic weights and are representative of the voting power of the relevant criteria (Figueira et al., 2013), rendering them suitable for integration with ELECTRE III method and thus justifying the use of these two methods together. Finally, there is evidence that the combination of BWM and ELECTRE III is helpful for manufacturing unit location selection (Makarevic & Stavrou, 2022), which is an MCDM problem that arises after choosing a focus area. This implies that applying BWM and ELECTRE III on the problem of finding a focus area will complement this existing research and in turn yield a useful framework for companies to use from the beginning until the end of process optimization implementation within manufacturing units in the supply chain.

3. METHODOLOGY

3.1. Interviews

In choosing the relevant decision-makers who were interviewed, several factors needed to be considered in order to assure the reliability of the results. First, it was important that the decision-makers hold different positions within the company, so that they could represent preferences of different company sectors. On top of this, it was important that they have spent enough time in the company to be familiar with the relevant products and processes, so that they could effectively assess the importance of the criteria. The relevant company sectors and the employees within them were identified by stakeholder mapping, which was done based on company documentation, as well as daily experience in the company. After this, a power/interest grid was constructed to make sure that the chosen decision-makers had power to influence the problem at hand, as well as interest in tackling it.

As mentioned previously, the interviews were conducted in two rounds. Both interviews were carried out with all the chosen decision-makers at the same time and were composed as semi-structured interviews (Kallio et al., 2016). Semi-structured interviews represent a combination of structured and unstructured interviews, as the interviewer does have the questions pre-made, however the questions are composed in an open-ended manner, enabling more flexibility (George, 2022). This was done in order to assure that each decision-maker can freely express their preferences, and so that ultimately the agreed upon preferences were indeed representative of the whole company. Furthermore, a rigid interview structure is not beneficial when stakeholders with different roles in the company are brought together with the end goal being them reaching an agreement. This method of conducting interviews is also in line with enabling group-decision making through sharing (Belton & Pictet, 1997)

The two interviews were organized as face-to-face sessions lasting 1 hour each. The first 15 minutes of the sessions were allocated for explaining the methodology, the goals and the outputs that needed to be collected.

The aim of the first interview was formulating one set of relevant criteria for the MCDM problem. First, the criteria from the literature were presented to the decision-makers. They were then asked to assess together whether those criteria were relevant to the specific issue, as well as if there are certain criteria that should be added to the set, some of which were suggested by the interviewer based on her findings from the company. The output of this interview was the final set of 7 criteria described in Section 4.4.

After the criteria was chosen, the data for BWM and ELECTRE III needed to be collected. The second interview once again involved the six relevant decision-makers. This time, the two methods and the kind of information they needed to provide for the analysis were explained. More specifically, the meaning behind the numbers ranging between 1 and 9 for BWM vectors was clarified, as well as the preference, indifference and veto thresholds for ELECTRE III. The decision-makers then together discussed their preferences, eventually agreeing on the values assigned to the criteria for BWM, as well as the thresholds for ELECTRE III.

3.2. Linear BWM

This section describes the steps of Linear BWM, formulated by Rezaei (2015, 2016). The steps are as follows:

Step 1: The set of relevant criteria $(c_1, c_2, \ldots, c_n)$ is presented to the decision-makers.

Step 2: The decision-makers are asked to select the best and the worst criteria from the set $(c_1, c_2, \dots, c_n)$, according to their preferences.

Step *3:* The decision-makers are asked to assign values ranging from 1 to 9 to express their preference of the best criterion over the other criteria from the set. This information is then used to form the Best-to-Others vector A_B:

$$A_B = (a_{B1}, a_{B2}, \dots, a_{Bn})$$

where a_{Bj} is the preference of the best criterion (B) over criterion j. Here, the value of 1 indicates that the chosen criterion is equally important as the best criterion, and the value of 9 indicates that the best criterion is extremely more important than the criterion in question

Step 4: The decision-makers are asked to assign values ranging from 1 to 9 to express their preference of the criteria from the set over the worst criterion. This information is then used to form the Others-to-Worst vector A_W:

$$A_W = (a_{1W}, a_{2W}, \dots, a_{nW})^T$$

where a_{jW} is the preference of the criterion j over the worst criterion (W).

Step 5*:* The optimal weights $(w_1^*, w_2^*, \dots, w_n^*)$ are calculated. This is done by computing a solution where the maximum differences of $\left|w_B - a_{Bj}w_j\right|$ and $\left|w_j - a_{jW}w_W\right|$ are minimized. This step corresponds to the mathematical model that follows:

$$\min max_j\{ \left|w_B - a_{Bj}w_j\right|, \left|w_j - a_{jW}w_W\right| \}$$

such that

$$\sum_j w_j = 1,$$

$$w_j \geq 0, for\ all\ j.$$

which is equivalent to:

$$\min \xi,$$

such that

$$\left|w_B - a_{Bj}w_j\right| \leq \xi, for\ all\ j,$$

$$\left|w_j - a_{jW}w_W\right| \leq \xi, for\ all\ j,$$

$$\sum_j w_j = 1,$$

$$w_j \geq 0, for\ all\ j.$$

The solution of this model are the optimal weights $(w_1^*, w_2^*, \dots, w_n^*)$ and ξ^*.

Step 6: The consistency ratio CR is calculated according to Liang et al. (2020) as follows:

$$CR = \max_j CR_j$$

where

$$CR_j = \begin{cases} \frac{|a_{Bj} \times a_{jW} - a_{BW}|}{a_{BW} \times a_{BW} - a_{BW}}, & a_{BW} > 1, \\ 0, & a_{BW} = 1. \end{cases}$$

Then, the consistency ratio is compared to the threshold values for input-based BWM presented below in Table 2 (Liang et al., 2020).

Scales	Criteria						
	3	4	5	6	7	8	9
3	0.1667	0.1667	0.1667	0.1667	0.1667	0.1667	0.1667
4	0.1121	0.1529	0.1989	0.2206	0.2527	0.2577	0.2683
5	0.1354	0.1994	0.2306	0.2546	0.2716	0.2844	0.2960
6	0.1330	0.1990	0.2643	0.3044	0.3144	0.3221	0.3262
7	0.1294	0.2457	0.2819	0.3029	0.3144	0.3251	0.3403
8	0.1309	0.2521	0.2958	0.3154	0.3408	0.3620	0.3657
9	0.1359	0.2681	0.3062	0.3337	0.3517	0.3620	0.3662

Table 2: Thresholds for input-based BWM (Liang et al., 2020)

3.3. ELECTRE III

This section describes the computational steps of ELECTRE III, formulated by Roy (1978, 1991).

In ELECTRE III, the preferences are modeled by making use of outranking relations (S), which means 'at least as good as'. Furthermore, a preference relation incomparability (R) is introduced. If there are two alternatives a and b, then there are four possible cases (Figueira et al., 2016):

1. aSb and not bSa, that is a is preferred to b ($a \succ b$)
2. bSa and not aSb, that is b is preferred to a ($b \succ a$)
3. aSb and bSa, that is a is indifferent to b (aIb)
4. Not aSb and not bSa, that is a is incomparable to b (aRb)

The basis for an outranking relation is in two key concepts (Figueira et al., 2016), namely:

1. Concordance: "For an outranking aSb to be validated, a sufficient majority of criteria should be in favor of this assertion."
2. Non-discordance: "When the concordance condition holds, none of the criteria in the minority should oppose too strongly to the assertion aSb."

All ELECTRE methods consist of two main procedures, namely aggregation and exploitation. Aggregation involves the process of making the outranking relations so that the alternatives can be compared, whereas aggregation refers to the results, i.e. the ranking/choice/sorting of the alternatives (Figuiera et al., 2016). In further text, Steps 1-4 refer to aggregation, and step 5 corresponds to the exploitation procedure.

Step 1: The decision-makers are asked to assign values to their preference (p_j), indifference (q_j) and veto (v_j) thresholds.

Step 2: For every pair of the alternatives a and b, the concordance indices $C(a,b)$ are calculated as follows:

$$C(a,b) = \frac{1}{W}\sum_{j=1}^{n} w_j c_j(a,b)$$

where

$$W = \sum_{j=1}^{n} w_j$$

$C(a,b)$ always has a value in between 0 and 1. If $C(a,b)$ = 0, the alternative a is worse than the alternative b, with respect to all the criteria in the set. $c_j(a,b)$ is the comparison index for every criterion j, and it is computed based on the performance of the alternatives.

Case 1 If alternative a is either equivalent to or better than alternative b minus the indifference threshold for criteria j:

$$c_j(a,b) = 1 \; if \; \mathrm{g_j}(a) + q_j(g_j(a)) \geq \mathrm{g_j}(b)$$

Case 2 If the performance of alternative a plus the performance threshold is less than the performance of alternative b, then alternative a is not better than b with respect to this selected criterion:

$$c_j(a,b) = 0 \; if \; g_j(a) + p_j(g_j(a)) \leq g_j(b)$$

Case 3 In all other cases:

$$c_j(a,b) = \frac{g_j(a) - g_j(b) + p_j(g_j(a))}{p_j\left(g_j(a)\right) - q_j(g_j(a))}$$

Step 3: The discordance index ($D(a,b)$) is computed. Its purpose is to utilize the veto threshold (v_j) and consider the cases in which one alternative is better than the other in general, but there is one or more (veto) criteria where it performs worse than the other alternative. The calculations are as follows:

Case 1 If alternative b is not better than alternative a by a more than v_j:

$$D_j(a,b) = 0 \; if \; g_j(b) \leq g_j(a) + p_j(g_j(a))$$

Case 2 If alternative b is better than alternative a by a more than v_j:

$$D_j(a,b) = 1 \; if \; g_j(b) \geq g_j(a) + v_j$$

Case 3 In all other cases:

$$D_j(a,b) = \frac{g_j(b) - g_j(a) - p_j(g_j(a))}{v_j - p_j(g_j(a))}$$

Step 4: The credibility ($S(a,b)$) is computed by combining the results obtained from the concordance and discordance calculations in the following manner:

Case 1 If there is no discordance or veto threshold:

$$S(a,b) = C(a,b)\ if\ D_j(a,b) \leq C(a,b), \forall_j$$

Case 2 In all other cases:

$$\mathrm{S}(a,b) = \mathrm{C}(a,b)\prod_{\mathrm{j}=1}^{\mathrm{n}}\frac{1 - D_j(a,b)}{1 - C(a,b)}$$

Step 5: The ultimate ranking is determined by evaluating the performance of each option in the preceding steps. Specifically, whenever alternative a surpasses alternative b, it receives a score of +1, whereas the other one receives a score of -1. Once all scores are summed up, a final score is calculated, which decides the ranking.

4. APPLICATION

The first step in conducting an MCDM analysis within a company is acquiring a full understanding of the company structure, the way it operates and who are the key decision makers. This part of the analysis is crucial when the company in questions is large and complex. The following sub- sections describe Philips, first from a high-level perspective and then narrowing down to the focus point of this project, which is the assembly process of the Floor Stand of the IGT Systems that is carried out in the Manufacturing Unit for IGT Systems in Best, The Netherlands. Next, the key decision-makers that will be involved are determined by making use of tools such as Stakeholder mapping and Power/Interest grid. Finally, the alternatives and criteria that will be used in the analysis are presented and described in detail, as well as the process of reaching the final set of relevant criteria.

4.1. The company

4.1.1. Company structure

Philips is highly customer-oriented, and for this reason the whole company is structured in terms of application domains. Namely, according to patient needs, the three Business Clusters within Philips are Personal Health, Diagnosis & Treatment, and Connected Care. The thesis project is carried out within the Image-Guided Therapy (IGT) Business which is part of the Business Cluster Diagnosis & Treatment.

Over the past few decades, image-guided therapies have quietly revolutionized the healthcare industry, shifting away from invasive surgeries that required lengthy hospital stays to minimally invasive procedures that allow patients to go home as early as the next day or in some cases even on the same day. These minimally invasive procedures, performed with catheters or needles and guided by advanced medical imaging technologies such as X-ray, MR, CT and ultrasound, typically require small incisions no larger than a pencil point. Clinicians use these images and navigation software to guide their instruments through the patients' body and perform procedures with the best possible outcome. Image-guided therapy procedures offer significant benefits for healthcare systems and patients, some of which are reduced patient trauma, shorter times of recovery as well as hospital stays, faster patient throughput and lower healthcare costs, which is driving their global growth. In the field of image-guided intervention, Philips IGT Systems is one of the global leaders in innovation (Philips, 2020).

The IGT Business relates to image-guided minimally invasive treatments and can be further split into IGT Devices and IGT Systems. IGT Devices refer to a range of advanced tools and technologies that are specifically designed to drive innovation in minimally invasive, interventional procedures within various clinical domains. For instance, Intravascular Ultrasound (IVUS) is a prime example of IGT Devices, as it generates images from inside blood vessels (arteries and veins) in the body. These images help clinicians to determine the most suitable therapy option, plan procedures beforehand, and verify and enhance treatment outcomes. The IGT Devices Business can be separated into 3 Segments according to the application of the devices, namely Coronary, Peripheral Vascular and Heart Rhythm Management.

IGT Systems Business on the other hand offers a portfolio of fully integrated health systems that are composed of interventional X-ray systems, as well as software solutions that make it possible for doctors to treat patients by making use of minimally invasive procedures that are personalized to them. IGT Devices enhance the functionality of IGT Systems by integrating navigational tools like catheters and guide wires with advanced software to facilitate optimal treatment guidance and confirmation at the point of care. Together, these components collaborate to guide procedures that are minimally invasive with improved effectiveness.

4.1.2. IGT Systems

Within IGT Systems, a distinction can be made between Fixed and Mobile Surgery solutions, depending on the customers' needs. The series including Fixed systems is named Azurion, while the Mobile systems are within the Zenition series. The focus of the thesis project is on the system that is part of the Fixed (Azurion) Systems.

An Azurion IGT System as shown in Figure 2 consists of the following main elements: a stand with an X-ray tube and detector, a patient table and a monitor used to project images.

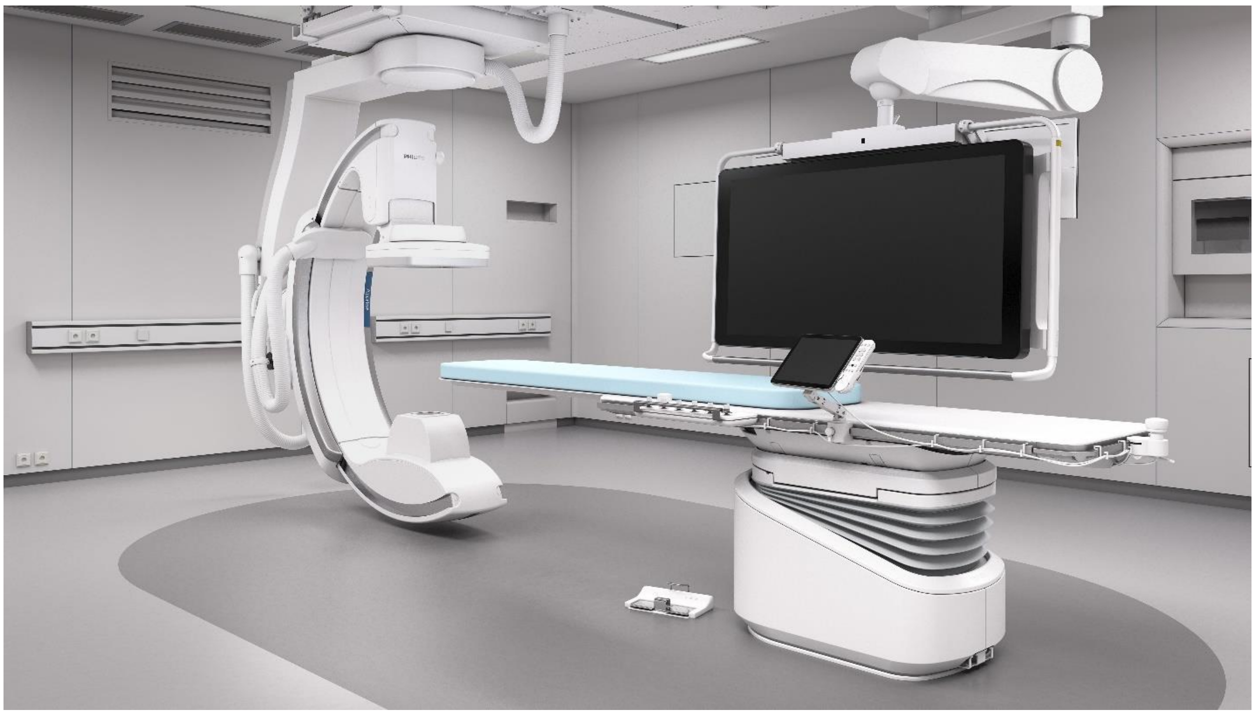

Figure 2: Azurion IGT System

There is a variety of Azurion systems which are carefully tailored according to the needs of the customers and patients that they should fulfill. This means that there are different benefits for different fields brought by Azurion. For *interventional cardiology*, the possibility to control the tools for both therapy and diagnostics by means of a single touch screen aids in making fast and informed decisions in crucial moments without having to break sterility. In *interventional radiology*, Azurion's integrated lab enables saving time by making advanced 3D tools within the SmartCT software, as well as intra-vascular imaging (IVUS) easily accessible. For *image-guided surgery*, simple and flexible control of the workflow from the table-side is one of the key benefits brought on by Azurion (Philips, n.d.).

The specific products within the Azurion portfolio can be differentiated according to several parameters. The key ones are reflected in the name of the system and these are the type of the flat detector (12'', 15'' and 20''), the indication on whether the system is ceiling-mounted (C), floor-mounted (F) or organized in a bi-plane manner (B), as well as the number 3, 5 or 7 which indicates the version of the system. Based on these characteristics, some of the available Azurion models are Azurion 3 F12, Azurion 3 F15, Azurion 5 C12, Azurion 5 C20, Azurion 5 F20, Azurion 7 B20/15, Azurion 7 C12, Azurion 7 F12 and Azurion 7 F20. Each of these systems is highly customizable and so aside from the aforementioned 3 parameters, there are many different add-ons that can be incorporated into them according to customers' needs and preferences.

4.1.3. Azurion Floor IGT System Stand

The scope of the project was narrowed down to the assembly process of one specific part of the systems namely the stand of the floor-mounted Azurion systems with a rotation point on the floor. Figure 3 below illustrates the stand that is the scope of the thesis project.

Figure 3: Floor Stand from the IGT System

This type of a stand (with the floor arm) can be found in multiple Azurion Systems, and the steps for the assembly that are carried out in the manufacturing unit are the same for all the systems of this kind.

In order to analyze this process sufficiently and accurately, it is important to have an in-depth understanding of the process flow and all the process steps that are being done within the manufacturing unit.

4.1.4. IGT Systems Manufacturing Unit

The assembly of IGT Systems is carried out in Philips's Manufacturing Units, where the systems are assembled by one or two factory operators at a time. There is a detailed, pre-defined and documented, stepwise procedure that is followed by the operators for each system. This procedure is enclosed in documents named 'Work instructions', that are written by employees working in the Manufacturing sector of Philips IGT Systems and are based on the System design provided by R&D employees. These documents include exact steps for the assembly. By carefully studying the Work instructions and observing the operators on the factory floor, it is possible to gain complete understanding and collect information about each step of the assembly process. Deconstructing the process into steps makes it easier to analyze the whole process and identify the most promising focus area of the current process accordingly. For this reason, the alternative focus areas used in the MCDM analysis are the process steps of the Azurion Floor Stand assembly.

4.2. Decision-makers

4.2.1. Organization Structure

Royal Philips is the parent company of the Philips Group and is governed by a Board of Management. This Board of Management is overseen by a Supervisory Board that is independent from Philips. To assist the Board of Management in fulfilling their managerial responsibilities, certain key officers from various functions, businesses, and markets have been appointed. Together with the Board of Management, these key officers form the Executive Committee.

Under the leadership of the Chief Executive Officer, the Executive Committee plays a vital role in executing Philips's strategies and policies and fulfilling its goals and results.

4.2.2. Stakeholder map

Figure 4 represents a simplified stakeholder map that depicts all the branches of Philips that are involved with the process that will be analyzed in order to determine the focus area for optimization. In other words, the decision-makers involved with the changes to be implemented with respect to IGT Systems are located within these areas of the company. Each square on the stakeholder map indicates a specific position within Philips. These positions are in some cases held by multiple employees, so the stakeholder map is not representative in terms of number of people involved, but rather serves as a tool which provides an overview of the variety of involved stakeholders. The information regarding the structure and involvement in the process analyzed was gathered through a number of meetings and interviews with different employees within Philips, as well as company documentation.

From left to right, three main branches within the organization structure can be clearly distinguished namely Manufacturing, IGT Systems R&D and Quality Assessment. This overview represents a starting point in choosing the relevant decision-makers whose preferences will be taken into account for carrying out the MCDM analysis. It is necessary that employees from each branch are involved in the decision-making process, so that the analysis represents the true preferences of the company and that, when the time comes, it is actually possible to implement the desired changes within the chosen focus area without experiencing pushbacks from the different stakeholders. Furthermore, sufficient involvement of stakeholders from all the branches ensures that all formal requirements and standards are taken into account in the implementation process.

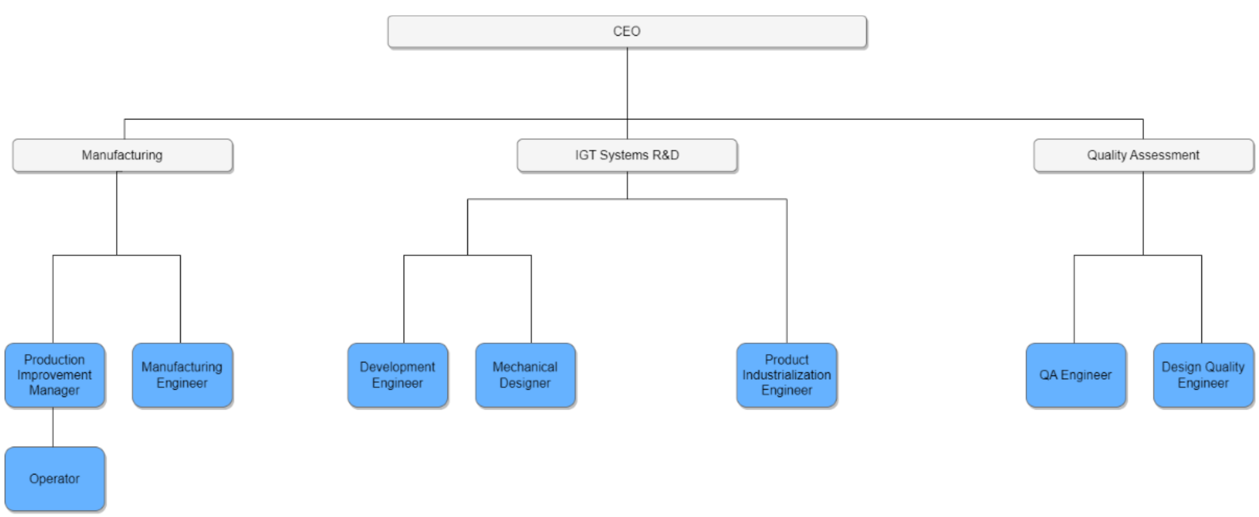

Figure 4: Simplified Stakeholder Map for IGT Systems decision-making

4.2.3. Power/Interest Grid

Power/Interest matrix, or power/interest grid created by Mendelow (1991), is a powerful tool in stakeholder mapping and stakeholder analysis overall, because it makes it possible to sort the stakeholders based on how much interest they have for the problem that is being addressed, but also how much power (influence) they possess for acting on it. Furthermore, this method is prescriptive, as it provides guidelines for stakeholder management based on their position in the grid. There are 4 pre-defined actions based on the level of power and interest related to the stakeholder and these are 'Manage closely,' 'Keep satisfied', 'Monitor' and 'Keep informed' (Markwick, 2000).

Figure 5 illustrates the Power/Interest grid for the relevant stakeholders in IGT Systems. It is important to note that the place of the stakeholders in the grid is determined according to how much interest they have and how much power they possess and are willing to exercise when it comes to implementing changes in the specific process of Azurion Floor Stand assembly. The main aim of constructing this graph is to arrive to a final list of the decision-makers that need to be involved in the MCDM analysis as key decision-makers. These decision-makers represent the preferences of Philips and they were interviewed in order to collect data for both BWM and ELECTRE III MCDM methods.

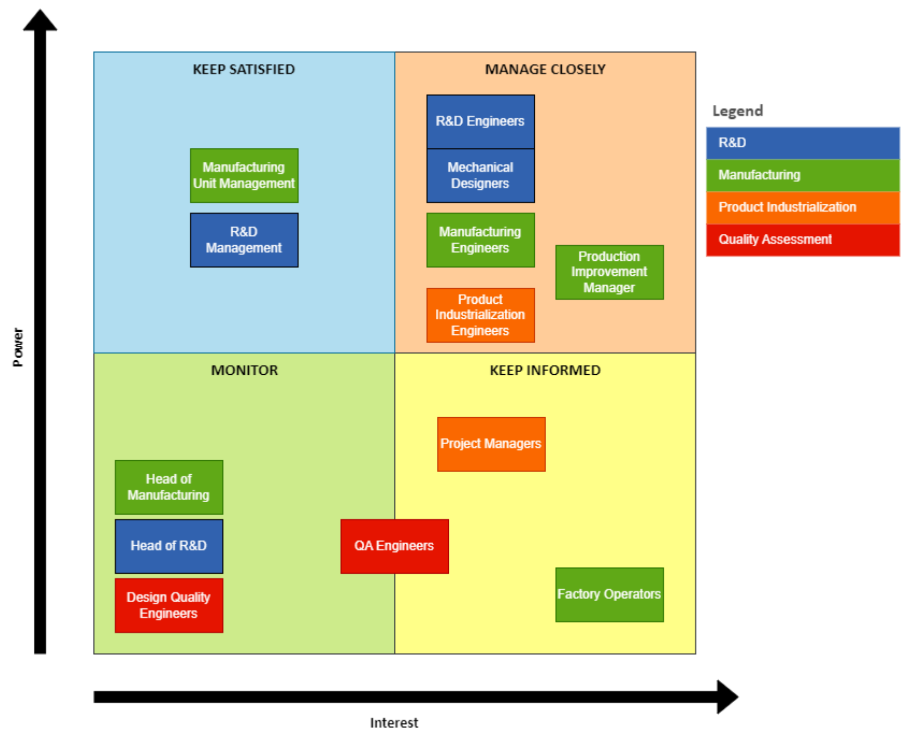

Figure 5: Power/Interest grid for stakeholders involved with IGT Systems

Several observations can be made from the Power/Interest grid. First, in the bottom left quadrant where stakeholders with both low power and interest are located, Heads of both the R&D Department and Manufacturing Department can be found. Although it might be expected that these actors hold more power, this is not the case due to the size and structure of the company. Namely, the head of such a large department is simply too far away in the chain of command to be closely involved in every decision-making process. Design Quality Engineers are in the same place of the grid because their involvement in the design process of IGT Systems is sometimes limited, as their input is really key after issues occur. The action suggested for managing these stakeholders is 'Monitor'. While the power is still considerably low, the interest level is higher for Quality Assessment (QA) Engineers. This stems from the fact that they come into contact with actual issues that occur on the factory floor. Having this in mind, it comes as no surprise that the stakeholders with the most interest and the least power in the grid are in fact Factory Operators. They are the ones most affected by the issues that occur in the factory, as they are the ones performing the assembly process. However, they do not hold much power, as they are located quite far away from decision-making in the organization structure. Project managers within Product Industrialization on the other hand have less interest but do hold more power due to the nature of their job. These three actors should be 'Kept informed' and they could play an important role as supporters of the potential project being developed. The quadrant for actors who hold a lot of power but have a low interest is occupied by R&D Management and Manufacturing Unit Management. These stakeholders have the power to make changes, so their needs should be met, and the main goal would be to also increase their interest. This is also implied in the action 'Keep satisfied' that is fit to this quadrant. Finally, the quadrant with actors who hold both high power and interest involves the engineers from R&D, Manufacturing and Product Industrialization, as these are usually enthusiastic and innovation-driven actors, whose knowledge and abilities also bring power to drive change. The actors involved with Production Improvement within the factory are also located in this area of the grid due to the enthusiasm and the fact that they have managing power within the manufacturing unit. The action corresponding to the actors in this quadrant is 'Manage closely'.

It is important to note that the actors could significantly shift around the power/interest grid, depending on the situation and that their positions in Figure 5 are only relevant for the power/interest they have when it comes to implementing changes in the assembly process of the Azurion Floor Stand. For instance, the Heads of R&D and Manufacturing normally do have more power than the rest of the actors involved as they can put a stop to any project, however in this particular case and at the time of the project, these actors were already informed on the goals of the project beforehand, so their further involvement was not required. However, if a new project was to be set up, their power would be much greater and they would need to be more involved.

4.2.4. Decision-makers chosen for the interviews

Based on the stakeholder mapping done in Section 4.2.2 and the power/interest analysis done in Section 4.2.3, six representative decision-makers were chosen.

First, it was determined that it is necessary to include actors from each of the three main branches outlined in the Stakeholder map in Figure 4. This scheme led to the formation of four categories that were then used to form the power/interest grid. The categories are depicted by different colours in Figure 5 and they are R&D, Manufacturing, Product Industrialization and Quality Assessment.

Next, it was decided to involve the stakeholders from the 'Manage closely' quadrant, as these actors are considered as 'key players' (Guðlaugsson et al., 2020), meaning that they need to be engaged and consulted frequently and heavily involved in the decision-making process. On top of this, it was decided to involve QA Engineers as well, so that the condition to include actors from each branch would be satisfied.

The professional roles of the decision-makers that will be interviewed are as follows:

- R&D Designer – generates the ideas and forms the designs of the Systems
- Development Engineer – implements the changes in the design

- Manufacturing Engineer – creates Work Instructions based on R&D input and tackles engineering processes in the Manufacturing Unit
- Product Industrialization Engineer – between R&D and Manufacturing Engineers, represents the Manufacturing Unit during the design process and reviews R&D designs
- Production Improvement Manager – manages the Manufacturing Unit operators, responsible for improvements in production processes
- QA Engineer – performs quality assurance practices in the factory

4.3. Alternatives

The set of alternatives chosen by Philips represents the possible focus areas where process optimization will be introduced first. The focus areas are all the steps that are being done in the Manufacturing Unit, in the assembly process of the Azurion Floor Systems Stand.

The steps are divided and named according to the main action that is being performed throughout the step. A detailed description of each step is not given due to confidentiality, as well as due to the nature of the research. Namely, as the focus is not on the engineering design and details of the process, it is not necessary for that kind of information to be included in this thesis project.

There are 8 steps and in order of assembly they are: Preparation, Mounting 1, Cabling 1, Mounting 2, Adjustment, Cabling 2, Testing and Mounting 3. Mounting refers to the attachment of smaller parts of the system such as the motor and covers onto the larger parts such as the stand and the floor arm. Cabling involves all routing and connecting of the cables for the system. Adjustment involves processes such as calibrating the X-ray, while Testing refers to the tests that are being carried out on the system in order to confirm that the assembly was performed correctly, and that the product meets the quality standards. It is important to note that there is no significant relationship between the 8 steps, although they are set up in sequence and together make up an integrated system. Namely, implementation of process optimization in one of the steps is not expected to influence the performance of other steps.

4.4. Criteria

The set of criteria that was used in the MCDM analysis of the issue within Philips was derived by combining the findings from literature discussed in Section 2.6 and discussions with different decision-makers within Philips in the first interview, as described in Section 3.1. In order to arrive to the final set of criteria, the criteria found in literature was first presented to the decision-makers. The main factor needed to be taken into account was that the existing literature mainly addresses specific problems with the alternatives in form of different locations, supplier companies and so on. In contrast, the alternatives in the case of Philips are process steps, which makes the criteria selection increasingly difficult, as it is not possible to assess certain criteria 'per process step', and some criteria are simply irrelevant for a stepwise perspective. These are criteria such as customer satisfaction, cost, compliance, reliability and so on. For the sake of more clarity, the decision-makers thought that it would be useful to select main criteria which would then be described by other criteria. So, *Flexibility*, *Requirements* and *Technology* were deemed the main criteria, described by a total of 7 criteria. These criteria are either taken directly from the literature or they were adjusted to fit the application.

A schematic overview is presented in Figure 6 below. All the criteria and the reasons for their selection are described in detail in the following sub-sections.

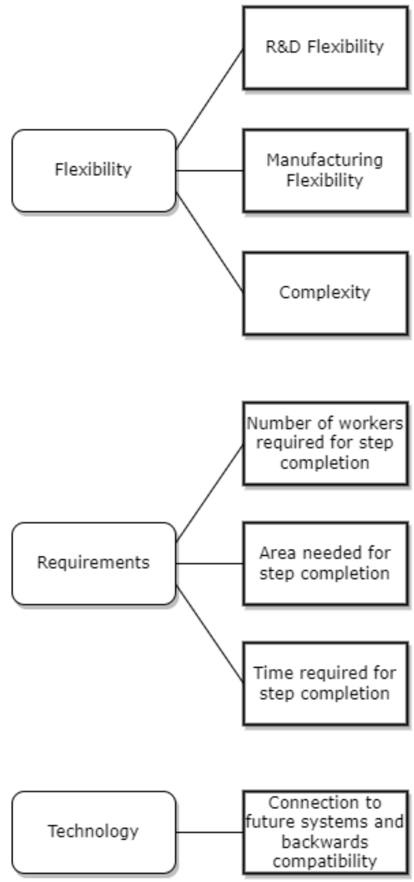

Figure 6: Criteria used in the MCDM analysis

4.4.1. Flexibility

An important factor to consider when deciding on where process optimization should be applied is *Flexibility*, as it addresses whether there exists an opportunity for implementing any changes within the process. Higher flexibility indicates that it is easier to introduce design improvements. In order to sufficiently assess this, the *Flexibility* criterion is assessed through 3 sub-criteria, namely *R&D Flexibility*, *Manufacturing Flexibility* and *Complexity*. R&D Flexibility indicates the willingness and ability of R&D to influence the step in question. The value of the criterion is assigned on a scale from 1 to 5, where 1 represents no willingness and ability from the R&D side and 5 stands for a high level of both willingness and ability for influencing the alternative from R&D. The values of this criteria are determined by knowledgeable decision-makers from IGT Systems R&D in Philips. In the same way, the values are assigned for Manufacturing Flexibility, but in this case, they are assigned by knowledgeable decision-makers from Manufacturing. The final criterion in the Flexibility cluster is *Complexity*. The higher the Complexity of the step, the lower the Flexibility, and vice-versa. Additionally, *Complexity* also addresses quality in the sense that a more complex step normally results in more mistakes i.e., more issues arise in the quality assessment process. This criterion also ranges from 1 to 5, but the values are assigned by decision-makers from both R&D and Manufacturing, based on how much complexity is there in the design of this step, as well as how much knowledge and practice are necessary to carry out the step on the factory floor. The value of 1 indicates a very low level of complexity, whereas 5 represents the opposite namely a very complex step to carry out and design. This means that the *Complexity* is inversely proportionate to the performance of the alternatives, namely it is desirable to have a low level of *Complexity* for process optimization. This property is considered and included in the computational steps of ELECTRE III.

4.4.2. Requirements

When dealing with complex manufacturing processes, certain requirements play a big part in carrying out process optimization. In this case, the *Requirements* criterion is defined by the sub-criteria *Number of workers required for step completion*, *Area needed for step completion* and *Time required for step completion*. These sub-criteria are crucial, as it is quite difficult to determine the cost per step in euros/another currency, and when tackling process optimization, cost minimization is normally one of the main goals of the whole process. So, the *Requirements* criterion also makes it possible to express the cost per step of the process in terms of human labor necessary, the area in m^2 and the time utilized for the particular step.

4.4.3. Technology

In healthcare technology industry it is necessary for technology to be incorporated into any kind of assessment. In the case of Philips, aside from implementing process optimization in the already existing process steps, it adds great value if some of the learnings from this particular issue can later be applied to similar systems within the portfolio, as well as to new, future systems. For this reason, the *Technology* criterion is expressed by *Connection to future systems and backwards compatibility*. The value for the alternatives when it comes to this sub-criterion are assigned by knowledgeable decision-makers within the company and range from 1 to 5. A score of 1 indicates that the step in question has no connection to other existing systems, nor the innovations planned for the future, whereas 5 indicates that it is certain that this step will be involved in the assembly of new planned systems and is already frequently seen in the currently-made systems.

The alternatives with the corresponding values of the criteria are presented in Table 3 below.

Process step	R&D Flexibility (1-5)	Manufacturing Flexibility (1-5)	Complexity (1-5)	Number of workers required for step completion	Area needed for step completion (m2)	Time required for step completion (min)	Connection to future systems and backwards compatibility (1-5)
Preparation	1	2	1	1	6	55	4
Mounting 1	2	3	2	2	6	190	3
Cabling 1	3	2	1	1	6	90	5
Mounting 2	3	3	3	1	6	185	4
Adjustment	1	4	5	1	6	40	5
Cabling 2	4	4	2	2	9	200	5
Testing	2	2	2	1	6	20	4
Mounting 3	1	3	3	1	6	40	3

Table 3: The alternatives and their performance according to the selected criteria

5. RESULTS

5.1. BWM

This section outlines the results obtained by following the steps for linear BWM (Rezaei 2015, 2016), as described in Section 3.2.

The values for the BWM vectors were achieved through consensus of the 6 decision-makers. The explanations of the criteria were supplied to them beforehand and were then briefly addressed once again at the beginning of the interview session. The first question posed to them was to decide on the Best and the Worst criterion. When choosing the Best, from the beginning there was a discussion on whether this should be *Complexity* or *Connection to future systems and backwards compatibility*. The interviewer then explained the meaning of these two criteria in more detail, so that the decision-makers would gain more clarity and possibly come to an agreement with more ease. The latter criterion was deemed very important as Philips is focused on constantly innovating and introducing new products. Furthermore, backwards compatibility plays a great role, as the company has been making significant efforts with respect to modularization and standardization of their systems. On the other hand, *Complexity* encompasses R&D, Manufacturing, as well as Quality. In healthcare technology industry, quality plays a crucial role, as there are a number of rules to comply with and it is extremely important that the number of mistakes is minimized, as the end users are human patients. For this reason, the decision-makers agreed on selecting *Complexity* as the Best criterion. The choice for the Worst one again was between two criteria, this time *R&D Flexibility* and *Manufacturing Flexibility*. The main reason for this was that it was deemed that if there is little flexibility in either sector, this is something that could be overcome and disregarded if the opportunity for improvement proved to be good enough with respect to other factors. Ultimately, the chosen one was *R&D Flexibility*, as one of the decision-makers pointed out that although the lack of both of these could be overcome if all the other criteria are satisfied, there could be some obstacles in Manufacturing that would not be possible to surpass.

After the choices for the Best and the Worst criterion were made, the decision-makers were asked to assign values ranging from 1 until 9 to all the criteria, with respect to the Best one (*Complexity*), which was assigned the value of 1. In the same manner, *R&D Flexibility* was then assigned the value of 9. Taking into account the previous discussion, the decision-makers decided that *Connection to future systems and backwards compatibility* should be given the value of 2, and *Manufacturing Flexibility* the value of 8, as these were both considered close in importance to the Best and the Worst, respectively. The three criteria used to describe the main criteria *Requirements*, namely *Number of workers required for step completion*, *Area needed for step completion* and *Time required for step completion* were said to be quite close in importance for the decision-makers, as they all describe what is necessary for the completion of the process steps. It was also pointed out that they are all considered much closer to the Best criterion than to the Worst. However, among the three, *Time required for step completion* was agreed upon as the most important, which is why it was awarded the value of 3. *Area needed for step completion* was discussed next among the interviewees and was awarded a 4, closely followed by *Number of workers required for step completion*, which was awarded a 5. The input from the decision-makers more involved with the operations carried out in the manufacturing unit was that the number of workers didn't matter as much, as it is quite flexible, namely the factory operators frequently help each other in carrying out the steps.

The input from the interviews was then organized to form The Best-to-Others and Others-to-Worst vectors for the computational steps of BWM, as presented below.

The Best-to-Others vector was formulated as follows:

Best to Others	R&D Flexibility	Manufacturing Flexibility	Complexity	Number of workers required for step completion	Area needed for step completion	Time required for step completion	Connection to future systems and backwards compatibility
Complexity	9	8	1	5	4	3	2

Table 4: Best-to-Others vector according to Philips's decision-makers

The Others-to-Worst vector was formulated as follows:

Others to the Worst	R&D Flexibility
R&D Flexibility	1
Manufacturing Flexibility	2
Complexity	9
Number of workers required for step completion	5
Area needed for step completion	6
Time required for step completion	7
Connection to future systems and backwards compatibility	8

Table 5: Others-to-Worst vector according to Philips's decision-makers

Based on the values of the Best-to-Others and Others-to-Worst vectors, the obtained weights of the criteria were as follows:

Weights	R&D Flexibility	Manufacturing Flexibility	Complexity	Number of workers required for step completion	Area needed for step completion	Time required for step completion	Connection to future systems and backwards compatibility
	0.0310	0.0543	0.3570	0.0869	0.1086	0.1449	0.2173

Table 6: Weights of the criteria according to Philips's decision-makers

The input-based consistency ratio (CR) calculated for this case was 0.2222. The threshold that this value is compared to is 0.3517 from Table 2 (Liang et al., 2020). As CR is lower than the threshold, the consistency level is deemed acceptable. The weights are also graphically depicted in Figure 7 below.

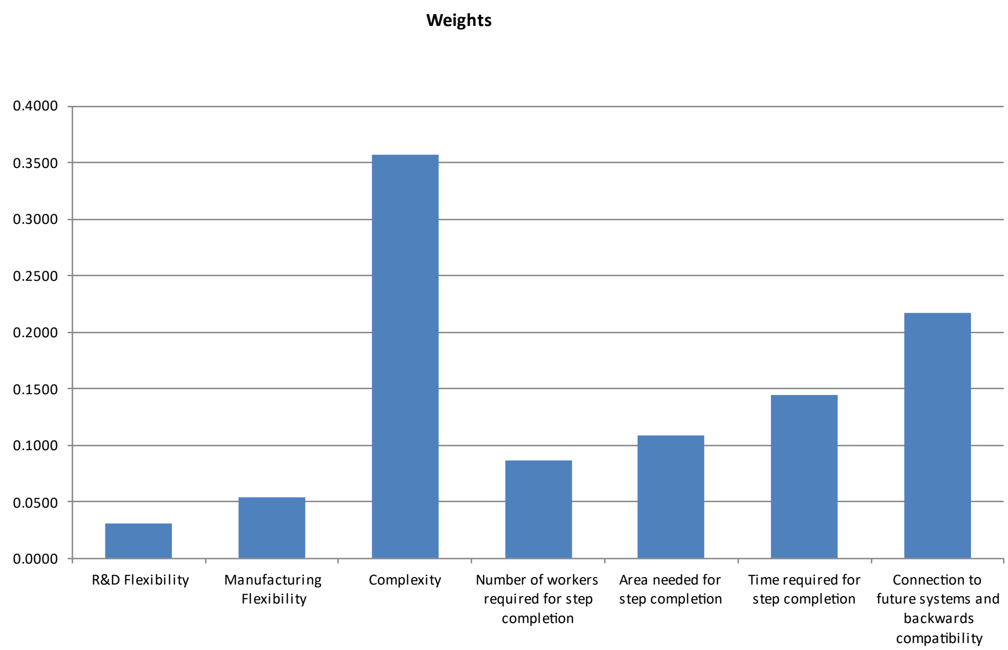

Figure 7: Weights of the criteria according to Philips's decision-makers

5.2. ELECTRE III

In this section, the results that were obtained by following the steps of ELECTRE III (Roy 1978, 1991) from Section 3.3 are presented.

The relevant decision-makers together supplied one set of preference (p), indifference (q) and veto (v) thresholds. The first step in collecting this data was a detailed explanation of the meaning of the different thresholds to the decision-makers. This step of the interviews required more involvement from the interviewer, as the decision-makers normally do not come across similar tasks in their day-to-day work. So, the interviewer provided examples of what certain values of the thresholds would imply in terms of decision-makers' preferences. There were no significant discrepancies and disagreements between the decision-makers with respect to assigning the values to the thresholds and once the method was well-explained, agreement was reached with no problems.

The assigned values of the thresholds are presented in Table 7 below.

	R&D Flexibility	**Manufacturing Flexibility**	**Complexity**	**Number of workers required for step completion**	**Area needed for step completion**	**Time required for step completion**	**Connection to future systems and backwards compatibility**
p	2.2	2.9	2.4	1.3	1.1	103	4.2
q	1	2	1	1	1	10	3
v	/	/	3	/	8	180	3

Table 7: Preference, indifference, and veto thresholds of the decision-makers in Philips

Not all criteria were assigned a value for the veto threshold (v). This is because the decision-makers determined that not all criteria do have veto power, but only those that are deemed important enough that above a certain level all other relations can be neglected.

The cutting level (λ) for the Credibility index was set to 0.7, in order to obtain more accurate results (Figueira et al., 2016). The credibility matrix that resulted from the ELECTRE III computational steps is presented in Table 8 below.

	Preparation	**Mounting 1**	**Cabling 1**	**Mounting 2**	**X-ray alignment**	**Cabling 2**	**Testing**	**Mounting 3**
Preparation	1	0.86	0.94	0.57	0.64	0.72	1	0.75
Mounting 1	1	1	1	1	0.64	0.87	1	1
Cabling 1	1	0.86	1	0.61	0.64	0.75	1	0.75
Mounting 2	1	1	1	1	0.75	0.88	1	1
Adjustment	0	0	0	0.83	1	0	1	1
Cabling 2	1	1	1	1	0.64	1	1	1
Testing	0.96	0.77	0.91	0.86	0.63	0	1	0.98
Mounting 3	0.99	0.86	0.91	0.83	0.75	0.65	1	1

Table 8: The Credibility matrix

After the Credibility matrix, the final ranking was obtained. The focus areas were ranked from 1 until 8, where 1 represents the alternative with the highest score. The ranking is the following:

1. Cabling 2
2. Mounting 2
3. Adjustment
4. Mounting 1
5. Preparation
6. Mounting 3
7. Cabling 1
8. Testing

6. DISCUSSION AND CONCLUSIONS

6.1. Discussion of the results

This section addresses the implications of the key results obtained from the MCDM analysis, namely the weights of the criteria from BWM and the ranking from ELECTRE III, as well as the process of discussing the results with the relevant decision-makers.

When it comes to the weights of the criteria computed by BWM, *Complexity* was deemed the best criterion by the decision-makers with the weight of 0.3570. This result is due to the fact that this criterion encompasses both the complexity from R&D's point of view, as well as Manufacturing. Furthermore, it also addresses quality, which is a very important factor when it comes to healthcare, as there are numerous standards that need to be met. The criterion that has the second-highest weight at 0.2173 was *Connection to future systems and backwards compatibility.* This result could stem from the fact that Philips is an innovation-driven company in a highly competitive industry. Namely, in order to gain/maintain competitive advantage, the company needs to constantly look ahead into the future and make improvements that will remain valuable in the long term. In the case of process optimization, it makes sense to focus on a process that will be present in future systems, as these new systems will eventually substitute the ones currently in place. Even if this is not the case, being able to reuse the same practices in multiple systems that are already being produced increases the modularity of the systems and so makes the company more adaptable to the fast-changing environment. The next criterion by weight is *Time required for step completion* with a weight factor of 0.1449, which is closely followed by *Area needed for step completion* with the weight of 0.1086. These two criteria both address the resources required for each step of the process, so it makes sense that they would be ranked high, as one of the main goals of process optimization is always cost minimization, and cost in terms of area and time is expressed through these two criteria. The fifth criterion according to the weight is *Number of workers required for step completion*, with the weight of 0.0869. Although this criterion is also a measure of cost, but in terms of human labor necessary, it is not considered as important as the two aforementioned ones. The reason for this is that although there is an exact number of workers necessary for the step, some steps are often performed with more workers than necessary anyway, in order to save time. So, it makes sense that *Time required for step completion* precedes this criterion in terms of importance (weight). The two criteria with the lowest weights are *Manufacturing Flexibility* and *R&D Flexibility*, with weights of 0.0543 and 0.0310, respectively. This means that *R&D Flexibility* was deemed the worst criterion by the decision-makers. The main reason for this could be that decision-makers consider these criteria as something that can be overcome. For instance, the R&D department possesses the necessary competences to tackle challenging projects that have to do with steps that are regarded as highly inflexible, and their willingness to do so is subject to change if something proves to be a good opportunity for improvement. The same goes for the manufacturing sector.

As the chosen criteria in great part stemmed from existing literature, the weights computed based on the preferences of the decision-makers in Philips were also compared to the weights in the literature, and several observations can be made. Ghaleb et al. (2020) conducted an MCDM analysis for manufacturing process selection and made use of seven criteria, including *Complexity* and *Flexibility.* In their analysis, these two criteria were found to have very similar weight factors, namely 0.104459 and 0.102623 respectively. Furthermore, these criteria were located in the middle with respect to the weights of the other criteria in the study. This is quite a significant difference, as *Complexity* was deemed as the most important criterion by Philips, and *Manufacturing Flexibility* and *R&D Flexibility* were regarded among the least important ones. Tam and Tummala (2001) use the criteria *Future technology development* and *Interoperability with other systems* which can be considered as equivalent to the criterion of *Connection to future systems and backwards compatibility* in the case of Philips. In the analysis of Tam and Tummala (2001), *Future technology development* and *Interoperability with other systems* are ranked as 13 and 18 respectively, based on their weights and out of 26 chosen criteria. This result also represents quite a discrepancy from the ones obtained in this analysis, as the criterion *Connection to future systems and backwards compatibility* was considered as the second most important one, closely following *Complexity* in terms of weight. These differences could stem from the company culture and structure, as well as the fact that every MCDM issue is unique and very complex. Furthermore, it is also important to note that the set of relevant criteria for Philips represents a combination of criteria from existing literature and criteria deemed relevant by the decision-makers, and so although it is interesting to observe the differences between literature and real-case application, it is difficult to draw conclusions when the sets of criteria are in fact different.

The ranking that resulted from ELECTRE III, placed Cabling 2 as the number one focus area for process optimization. This alternative had the second-best score possible (2) with respect to the best criterion, *Complexity*. Furthermore, in comparison to the other alternatives, it also performed the best in the three highest-weighing criteria following the best one, namely *Connection to future systems and backwards compatibility, Time required for step completion* and *Area needed for step completion*. Therefore, it is clear why it was ranked first. The process step that was ranked last is Testing. This step performed poorly with respect to almost all the most important criteria.

This ranking was discussed with the six relevant decision-makers, in order to gather opinions on the outcome of the analysis and to explore whether the actual outcome was in line with their expectations. The overall opinion was that the step that was ranked first (Cabling 2) was expected to be one in need of optimization due to easily observable factors on the factory floor, such as how much floor area is occupied during its completion, as well as how much time is needed for carrying it out. However, it is important to note that although it is possible to observe the performance of the steps with respect to criteria *Area needed for step completion* and *Time required for step completion* daily on the factory floor, these were in fact not the criteria with the highest weights. As mentioned, the Cabling 2 step also scored high when it comes to the highest weighing criteria, which is what ultimately led to its high ranking, together with the high scores in other criteria. The decision-makers deemed the analysis insightful overall and thought that it was interesting to be able to observe and assess the performance of the process steps based on the criteria that are not so apparent at first.

6.2. Strategies and recommendations for the company

Based on the ranking results, the overall recommendation for Philips would be for them to implement process optimization within the Cabling 2 step of the assembly process. The first step in this process would be to explore ways in which this could be done. For instance, a brainstorm with R&D and Manufacturing Engineers could be organized in order to foster idea generation for possible solutions. From these ideas it would then be possible to select a set of most promising solutions, which could then be considered as a new set of alternatives for another MCDM analysis. The outcome of the analysis would then be the ranking of specific solutions for process optimization within the Cabling 2 process step. Of course, it is important to note that the set of relevant criteria in this case would significantly differ from the one used in determining the focus area for process optimization.

In any case, one of the most important steps before implementing a specific solution for process optimization is assessing the feasibility of the solution. Namely, it is necessary to carry out a thorough financial analysis in order to sufficiently determine both the costs and the benefits that stem from the chosen solution. The financial feasibility could also already be taken into account when choosing the relevant criteria for Cabling 2 process optimization through one or more measurable criteria, as this was not possible in the MCDM analysis related to choosing the focus area, due to the nature of the alternatives, so cost was expressed through the *Requirements* criterion.

Finally, in case that the company decides to look for an additional focus area for process optimization later in the future, the analysis such as the one carried out in this research should be done again from the beginning. This means that the choice of criteria, their weights, as well as the performance of the alternative focus areas should be reassessed, as the healthcare technology industry is a dynamic one and the various qualitative and quantitative parameters can vary over time. On top of this, the choice of relevant decision-makers should be reassessed as well, by means of performing stakeholder mapping and constructing a new power/interest grid depending on the scope of the new project.

6.3. Theoretical and practical contributions

This thesis contributes to the existing research in the fields of supply chain management and MCDM on several levels. First of all, it addresses the research gap in finding a focus area for process optimization within manufacturing units. As far as it is known to the researcher, the combination of BWM and ELECTRE III applied to a real-life case is only addressed by one other research paper (Makarevic & Stavrou, 2022), and on a specific problem regarding location selection of a manufacturing unit, so not the step before i.e., the topic of this research. Furthermore, BWM is a novel MCDM method that has been deemed promising, and its application on real-life cases adds to its further verification. On top of that, a major contribution of the decision-making approach that involves a combination of BWM and ELECTRE III lies in the compatibility of these two methods. Namely, the weights that are given as the output of Linear BWM can be considered intrinsic, i.e. represent the voting power of the criteria (Figueira et al., 2013), as opposed to trade-off (compensatory) weights, which are incompatible with a method such as ELECTRE III. Compensatory methods yield weights that are interpreted as trade-offs, meaning that the criteria can be compared to each other and a higher performance of the alternative with respect to one criterion can compensate for a lower performance with respect to a different criterion (Banihabib et al., 2017; Majumder, 2015). This is not the case with intrinsic weights, as there is no compensation between the criteria (Figueira et al., 2013).

On a more practical level, the thesis offers a clear and straightforward framework for healthcare technology companies with a large portfolio of different product and processes within their supply chain, as well as a large number of employees distributed across different divisions of the company. By making use of the framework, it is possible to solve complex multi-criteria decision-making problems while satisfying multiple decision-makers with different preferences. The steps of this framework are fairly easy to replicate and make use of in companies other than Philips as well, and even in industries other than healthcare technology, as long as the relevant criteria are adjusted accordingly.

6.4. Limitations of the study and possibilities for further research

The choice of any MCDM method for the analysis could be argued both for and against. Naturally, the use of MCDM methods other than the ones chosen was considered. For instance, the use of AHP for both obtaining the weights and the ranking was considered, as this method is widely used for MCDM problems (Aziz et al., 2016). However, BWM utilizes a smaller number of pairwise comparisons and yields more consistent comparisons (Amiri et al., 2021). PROMETHEE was also considered for use instead of ELECTRE III, however ELECTRE III was said to outperform PROMETHEE (Majdi, 2013).

When it comes to the selected criteria, it is important to mention that *Flexibility* and *Technology* may not be fully objective because the values for the performance of the alternatives with respect to these criteria were assigned by people working within Philips, as opposed to the *Requirements* criterion, for which the values were measured by a device and can therefore be considered as objective.

The possibility of the presence of different kinds of cognitive and motivational biases must be addressed in the context of MCDM, as this can be a cause of distortion of the analysis of decision-making problems. Cognitive biases are defined by Montibeller and von Winterfeldt (2015) as "faulty mental processes that lead judgments and decisions to violate commonly accepted normative principles." A cognitive bias worth mentioning for this particular case is the anchoring bias. This bias could occur when there is a given initial value i.e. the anchor, that then serves as a basis for estimating the final answer (Tversky & Kahneman, 1974). Within the methods used in this research, the anchoring bias could be present in the elicitation of the weights. However, BWM does involve a debiasing strategy for anchoring, in that the weights are computed first based on the Best-to-Others vector, and afterwards on the Others-to-Worst vector. The weights cancel out the biasing effects leading to a less biased final answer. Motivational biases are "conscious or subconscious distortions of judgments and decisions because of self-interest, social pressures, or organizational context" (Montibeller & von Winterfeldt, 2015). Confirmation bias is a type of motivational biases that stems from the desire for confirming a belief of someone else, which results in unconscious selectivity with respect to gathering and using evidence (Nickerson, 1998). In the case of Philips, this bias is mitigated by involving multiple decision-makers with different roles and points of view in the decision-making process. Biases overall can also be classified in terms of who they affect namely there are individual and group biases. The aforementioned anchoring bias and confirmation bias are both individual biases. Although they are applicable to the decision-makers involved on an individual level, group biases must be mentioned as well, as the problem on hand is regarded as a group decision-making issue. One such bias that could have occurred in the analysis process is *Groupthink*. This bias tends to be present in cohesive groups whose main focus is achieving a consensus, no matter at what cost, which could lead to lack of realistically exploring different solutions (Janis, 1972). The suggested debiasing strategy involves the use of multiple decision-makers with different viewpoints (Montibeller & von Winterfeldt, 2018), which was done in the case of Philips.

Finally, when it comes to possibilities for further research, the effectiveness of other MCDM methods could be explored, as there is no literature addressing the issue of choosing a focus area. In addition to this, the combination of BWM and ELECTRE III could be applied to different cases, so that this approach is further validated. Furthermore, the elicitation of suitable criteria for supply chain management issues represents a good research opportunity. This part of relevant MCDM studies still remains without a clear framework, due to the fact that every MCDM issue is unique in terms of relevant qualitative and quantitative factors that are involved.

6.5. Conclusion and reflection

The main aim of this thesis was to present a framework for healthcare technology industry companies looking to choose a focus area for process optimization within a manufacturing unit. This was done by supplementing a new decision-making approach for group decision-making, which utilizes a combination of two MCDM methods namely Linear BWM for the elicitation of the weights of the relevant criteria and ELECTRE III for the ranking of the possible focus areas regarded as alternatives. Aside from the two MCDM methods, tools such as stakeholder mapping and power/interest grid were used to determine the relevant decision-makers who were involved in the analysis. In order to illustrate its effectiveness, the approach was applied to a real case, namely the assembly process of an Azurion Floor Stand, which is a stepwise process occurring within a manufacturing unit of Philips IGT Systems in The Netherlands, where I have completed my graduation internship as part of the IGT Systems R&D Department. The outcome of the analysis was the final ranking of the focus areas, where the Cabling 2 process step was ranked first, so the recommendation for Philips was to implement process optimization in this particular step. Overall, it can be said that the framework fulfills its purpose, while also contributing to the existing research in the field of MCDM and supply chain management.

During the course of this thesis project, I have learned a number of things. First, the literature study that was done for the thesis resulted in a significant deepening of my knowledge in the field of MCDM, as well as in conducting research overall. Another skill that this research has sharpened for me was that of conveying complex information to people who are not as familiar with the topic that is being discussed. Namely, this was both the case with writing the report in a manner that is clear to all the readers, no matter the academic background, as well as introducing the concept of MCDM in practice in Philips. Furthermore, the graduation internship I have done in Philips was my first experience in working full-time, which brought up many challenges, such as work/life balance and stakeholder management. The time I spent working in Philips made me gain significant tacit knowledge about communicating with co-workers and working in a dynamic and diverse environment. In summary, I feel that throughout this project I have improved a number of both hard and soft skills. Finally, if I were to do anything differently, it would be putting less pressure on myself at times and organizing my time in a better way at the beginning.

7. BIBLIOGRAPHY

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