JÖNKÖPING UNIVERSITY
School of Engineering

Developing a line balancing tool for reconfigurable manufacturing systems

A tool to support investment decisions

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This final thesis has been carried out at School of Engineering in Jönköping within the subject area production systems. The work is a part of the Master of Science program Production Development and Management. The authors take full responsibility for the opinions, findings and conclusions presented.

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Abstract

Purpose This thesis aims to developing a decision-making tool which fits in a reconfigurable manufacturing system (RMS) milieu used to identify whether to introduce and produce a new product into an already existing assembly line or to invest in a new assembly line. To fulfil the purpose, four research questions were developed.

Method Literature studies were performed in order to create a theoretical foundation for the thesis to stand upon, hence enabling the possibility to answer the research questions. The literature studies were structured to focus on selected topics, including reconfigurable manufacturing systems, line balancing, and assembly line investment costs. To answer the third research question, which involved creating a decision-making tool, a single-case study was carried out. The company chosen was within the automotive industry. Data was collected through interviews, document studies and a focus group.

Findings & Analysis An investigation regarding which line balancing solving-techniques suit RMS and which assembly line investment costs are critical when introducing new products has been made. The outputs from these investigations set the foundation for developing a decision-making tool which enables fact-based decisions. To test the decision-making tool's compatibility with reconfigurable manufacturing systems, an evaluation against established characteristics was performed. The evaluation identified two reconfigurable manufacturing system characteristic as having a direct correlation to the decision-making tool. These characteristics regarded scalability and convertibility.

Conclusions The industrial contribution of the thesis was a decision-making tool that enables fact-based decisions regarding whether to introduce a new product into an already existing assembly line or invest in a new assembly line. The academic contribution involved that the procedure for evaluating the tool was recognized as also being suitable for testing the reconfigurable correlation with other production development tools. Another contribution regards bridging the knowledge gaps of the classifications in line balancing-solving techniques and assembly line investment costs.

Delimitations One of the delimitations in the thesis involved solely focusing on developing and analysing a decision-making tool from an RMS perspective. Hence, other production systems were not in focus. Also, the thesis only covered the development of a decision-making tool for straight assembly lines, not U-shaped lines.

Keywords Reconfigurable manufacturing systems, Line balancing, Assembly lines, Case study, Decision-making tool

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Abbreviations

RMS	Reconfigurable Manufacturing System
FMS	Flexible Manufacturing System
DMS	Dedicated Manufacturing System
DMT	Decision-Making Tool
VSM	Value Stream Mapping
SMED	Single Minute Exchange of Die
SALBP	Single Assembly Line Balancing Problem
MMAL	Mixed-Model Assembly Line
MMALBP	Mixed-Model Assembly Line Balancing Problem
RPW	Ranked Positional Weight
KWC	Kilbridge and Wester Column
LCR	Largest Candidate Rule

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Glossary

Task / operation	Activity required to produce or assemble products or parts of a product
Station	Workplace within the assembly line where one or several tasks are performed
Task time	Required time to perform a task. Also referred to as cycle time.
Takt time	The rate in which a product needs to be completed in order to meet the customer demands

1 Introduction

The first chapter introduces the reader to the thesis background and problem description, which involves rapid changes in customer demand, forcing companies to re-evaluate their production systems to keep up with the increased product introduction rate. Based on this challenge, the purpose and research questions have been created. The later part in this chapter presents the thesis delimitations and outline.

1.1 Background

We are living in a dynamic world driven by globalization and rapid economic growth. Customer needs are changing fast, resulting in shorter product life cycles and a higher product introduction rate. This puts production systems into a tough competitive environment in responding to the fluctuation of market demand and consumption trends. To survive this thought-provoking situation, production systems adopt different strategies (Ulrich & Eppinger, 2016). Companies may rely on platform-based product strategy and product families by applying flexible manufacturing systems (FMS) through robots and computer numerical control (CNC) machines. However, these machines tend to be very expensive, have a high level of capital investment and are not capable of mass manufacturing (Dhandapani et al., 2015). As a response to price competitiveness, firms tend to pursue a low-cost strategy by using optimization tools that improve the system's productivity and performance. Production development tools such as lean production, value stream mapping (VSM), single-minute exchange of die (SMED) and line balancing have been used as drivers for companies' competitive advantage to thrive in the competition (Hallgren & Olhager, 2009; Jebaraj et al., 2013; Naor et al., 2010).

Reconfigurable manufacturing systems (RMS) have been presented as an approach to deal with the two-folded production capacity-product variety dilemma. The definition of RMS has been controversial. For instance, Koren et al. (1999) consider these as systems with the ability for rapid change of the production system, while Mehrabi et al. (2000) describe RMS as a stage between dedicated manufacturing systems (DMS) and flexible manufacturing systems (FMS). Nevertheless, researchers have agreed to describe RMS with some common characteristics. These regard scalability, customization, convertibility, modularity, integrability, diagnosability and mobility (Koren & Shpitalni, 2010; Maganha et al., 2019; Wiendahl et al., 2007). These characteristics support the production system's ability to respond to an increased product introduction rate. This can be achieved through a combination of changes, either in hardware, such as layout and equipment, or in logical planning and augmentation (Wiendahl et al., 2007). The second part of the dilemma regards cost reduction and productivity fluctuation. Line balancing has been used as a mathematical tool to design and calculate the efficiency of sequential operations for an assembly line. The operations in the assembly line are grouped within stations. The grouping is performed in order to distribute the workload by arranging tasks among production system's resources, which enables the possibility of coping with variation between machine capacities to match the overall production rates (Baybars, 1986; Hoffmann, 1963).

The early model for line balancing, developed by Salveson (1955), was created with the purpose of reducing waste, waiting time, inventory, and absorb irregularities within the system. Several mathematical models have since then been developed to solve the line balancing optimization problems. These models usually include calculating the number of stations and layout based on the line cycle time and task (operation) time for every operation. Line balancing facilitates an understanding of the dependency between processes and the identification of the bottleneck operation, which is needed in order to make assembly lines more efficient. Consequently, applying line balancing can lead to the relocation of resources and merging operations or modification of the layout (Hoffmann, 1963; Nallusamy, 2016).

1.2 Problem description

RMS has been gaining more attention during the last few years (Andersen et al., 2017). However, thus far the majority of RMS literature has primarily focused on configurations, constellations, concept development and technological aspects (Napoleone et al., 2018). Even though RMS was found able to deal with the issues with DMS and FMS, some concerns still exist with this type of production system, such as, optimization problems (Yelles-Chaouche et al., 2020). Hitherto this has been neglected in academia, and only a few mathematical models for streamlining line efficiency of RMS have been established in the literature. For instance, Saxena & Jain (2012) present a three-phased methodology to decide RMS configuration for a specific time period, and Jianping et al. (2007) adopts an economic perspective in RMS line configurations and presents a novel optimization model. The lack of optimization tools might derive from the relative newness of RMS and the complexity of these types of production systems.

Instead of developing completely new production development tools, updating and adapting already existing tools to fit in new production settings is an alternative. One of the most common tools in production is the renowned line balancing (Erel & Sarin, 1998). However, previous line balancing models and techniques have foremost been related to DMS, especially for a single product, and not developed specifically for RMS (Son et al., 2001). For example, in Bortolini et al. (2018), who conducted an extensive literature study on the research trends of RMS, found the optimization aspect in line balancing to be neglected entirely. Nonetheless, Yuan et al. (2019) have actually directly addressed the issue by developing a reconfigurable assembly line balancing optimization model, specifically for cloud manufacturing systems. However, as the focus in Yuan et al.’s (2019) research has been on cloud manufacturing, which many companies have not yet adopted, it cannot be applied to the overarching mass of companies. Hence the issue of non-existing line balancing optimization models still exists. Nevertheless, some improvements have been made, for instance, as a response to the aforementioned growing customer trend for a higher level of product variability, as well as the shorter product life cycles, the mixed-model assembly line balancing methods was developed (Bukchin et al., 2002; Cevikcan et al., 2009). This comparatively new type of line balancing is taking the production of several products from the same product family into consideration when enhancing the line efficiency (Olhager, 2013; Şeker et al., 2013), hence it can be recognized as suitable to use in RMS settings.

Even though the production efficiency dilemma might be solved through utilizing line balancing, and the second part of the dilemma, namely, how to tackle an increased product introduction rate can be resolved through the implementation of RMS, some issues still exist. Because, an increased introduction rate also forces decision-makers to more frequently make rapid and accurate decisions. One of these decisions, which is recurrently taken during the early phase of the new product development process, includes deciding how and where to produce new product variants (Wouters et al., 2009). These complications are creating uncertainties within investment decisions. Thus, during the early stages of the product development process, the decision-maker not only needs to answer questions regarding the product but also regarding potential production system investments, including capital and operational costs (Karsak & Tolga, 2001).

In order to simultaneously evaluate the compatibility of product variants through line balancing, whilst also investigating the potential investment costs of upgrading or investing in new production systems, the aforementioned two-folded dilemma would be solved. Hence, there is an apparent need for a tool which simultaneously integrates line balancing with investment cost calculations while operating in a RMS milieu. Such a tool would enhance the decision-making regarding whether a new product should be produced in an already existing assembly line or if investing in a new assembly line is the most economically beneficial option. Thus far, such a decision-making tool that combines these two perspectives has not previously been investigated in academia.

1.3 Purpose & research questions

Given the problem stated above, the purpose of this thesis is to:

Develop a decision-making tool which fit in a RMS milieu used to identify whether to introduce and produce a new product into an already existing assembly line or to invest in a new assembly line

To be able to fulfil the purpose, four research questions have been developed. The first research question is necessary in order to explore the theory regarding existing line balancing techniques:

1) **Which line balancing problem-solving techniques exist in the literature?**

In order to add the investment perspective when deciding whether to introduce a new product in an already existing assembly line or invest in a new assembly line, the second research question was developed. This was formulated as follows:

2) **Which investment costs can be considered vital for new assembly lines as a consequence from new product introductions?**

The third research question investigates the possibility of developing a decision-making tool which takes both the line balancing perspective and investment perspective into consideration. This was achieved by combining the theoretical knowledge gained from the previous research questions with data collected in the case study. Hence, the following research question was formulated:

3) **Can a decision-making tool be designed to evaluate new product introductions which considers both line balancing KPIs and investment costs in an assembly line?**

Lastly, as a means to evaluate the model and its connection to RMS characteristics, and thereby being able to discuss the primary academic contributions from this thesis, a fourth research question was developed:

4) **To what extent can criteria in the RMS theory be linked with the attributes of the designed decision-making tool to support its applicability?**

1.4 Delimitations

This thesis will solely focus on developing and analysing a decision-making tool from an RMS perspective. Hence, other major production systems, i.e. DMS and FMS, will not be in focus. Also, this thesis is only covers the development of a decision-making tool for straight line layout assembly lines. Other types of assembly lines, such as U-lines are thereby excluded. This delimitation was necessary since line balancing techniques and algorithms adapted for U-lines are not identical to the ones for straight assembly lines. Furthermore, the validation and testing of the decision-making tool (DMT) is based upon data provided from the case company. Thus, the authors will not collect any time measurements by themselves and solely rely on the basis that these are correct. Also, the decision-making tool will not be tested in a wider setting, with input from other companies. Further delimitations regard that the report only covers KPIs connected to line balancing and investment costs on an overarching level. This delimitation exists since the decision-making tool is intended as being modular, whereas users have the possibility to insert the most relevant KPIs and investment costs in their situation.

1.5 Thesis outline

The thesis consists of seven chapters, see Figure 1 below. The first chapter has served as an introduction of the topic and clarified the existing knowledge gap, presenting the thesis aim and research questions.

The second chapter covers the theoretical framework, beginning with describing the outlines of RMS, assembly line types and line balancing classifications. Thereafter, a generic procedure for developing a spreadsheet decision-making tool is touched upon. Lastly, the economic perspective in the form of key performance indicators, production investment costs and Monte Carlo simulation is presented.

The third chapter explains the methodological angle. Beginning in a wider setting and clarifying the research design. Thereafter the data collection methods used are presented. These includes literature studies, case study, interviews, document analysis and focus group. Furthermore, the procedure for testing and validating the DMT as well as how trustworthiness is taken into consideration, is clarified. Lastly, an explanation of how the ethical and moral perspective is taken into consideration in the thesis is presented.

The fourth chapter is presenting the theoretical findings for RQ1, RQ2 and RQ4. Whereas the former two are creating the foundation for developing the decision-making tool, and the latter necessary for understanding the correlation between RMS and the decision-making tool.

The fifth chapter in presenting the decision-making tool, i.e. the result from RQ3. This is initiated with a description of the decision-making tools outline, framework, applicability, and assumptions. Thereafter, a detailed declaration of the decision-making tool’s structure, computations and calculations are described. The chapter ends with a description of the feedback on the decision-making tool gained during the focus group.

The sixth chapter is commencing with an analysis and discussion of the four research questions. This is followed by a discussion of the applied method.

The seventh chapter begins with a presentation of the industrial and academic contributions. Thereafter, the thesis limitations, suggestions for further development of the decision-making tool, and future research topics are touched upon.

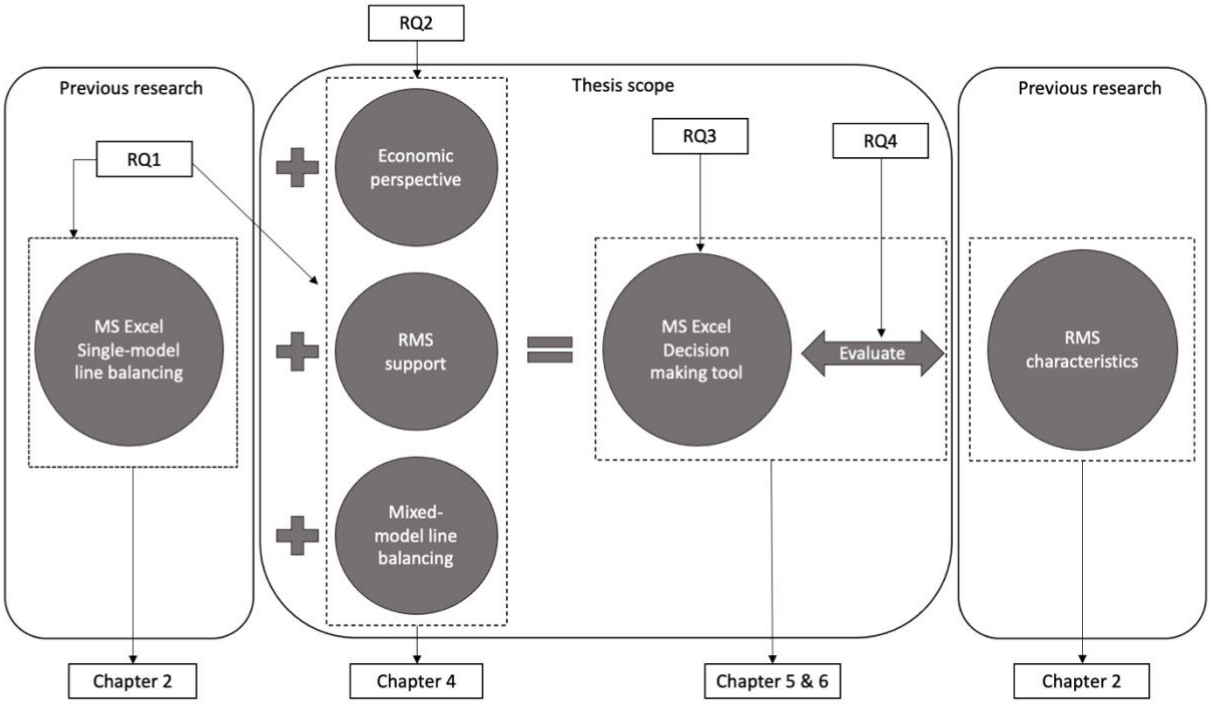

Figure 1 - Thesis structure and outline

2 Theoretical framework

The second chapter covers the thesis theoretical framework, beginning with describing RMS and associated classifications and characteristics. Thereafter, the line balancing and investment costs theory is presented.

2.1 Reconfigurable manufacturing systems

The complexity of modern industrial processes motivates the need to adapt a holistic perspective when designing or operating production systems. The main concern is that many researchers have underlined the interrelated relationship between the components and levels of the system (Bellgran & Säfsten, 2009). For instance, Groover (2016) highlighted that the production system consists of two core levels. One of these regard facilities, which include factories, machinery, material handling tools and so on. The other level regards the manufacturing support system, focusing on the soft part of the system. This includes standards, procedures, product design, and working schedules, etc. Manufacturing systems can further be categorized based on the systems' flexibility to handle changes in demand. According to Koren et al. (1999), manufacturing systems can be divided into three categories; DMS, FMS and RMS.

DMS are prepared with a set of machining and other material handling equipment which facilitates delivery of a product with specific features. Such a system targets to produce in mass capacity with very low variation in products or manufacturing process. The simplicity of the system requires workers with a minimum degree of skill. As a result of this, dedicated manufacturing systems are typically cost-effective when high demand with low product variety is expected (Bellgran & Säfsten, 2009). On the other hand, FMS are equipped with machinery which are able to handle products with a wide difference in features. This ability facilitates the possibility to produce complex products, which is not easily accomplished in DMS. The FMS usually contains CNC machines and a high level of automation. However, several drawbacks related to FMS have appeared. These drawbacks primarily regard long setup time to change between products and an extensive time-consuming maintenance (Koren et al., 2018). Nevertheless, improvements have been introduced to both DMS and FMS in order to avoid the lack of flexibility of the DMS and to increase the production capacity of FMS. These improvements created a space of solutions that are defined as RMS, as illustrated in Figure 2 (Koren, 2006; Wiendahl et al., 2007).

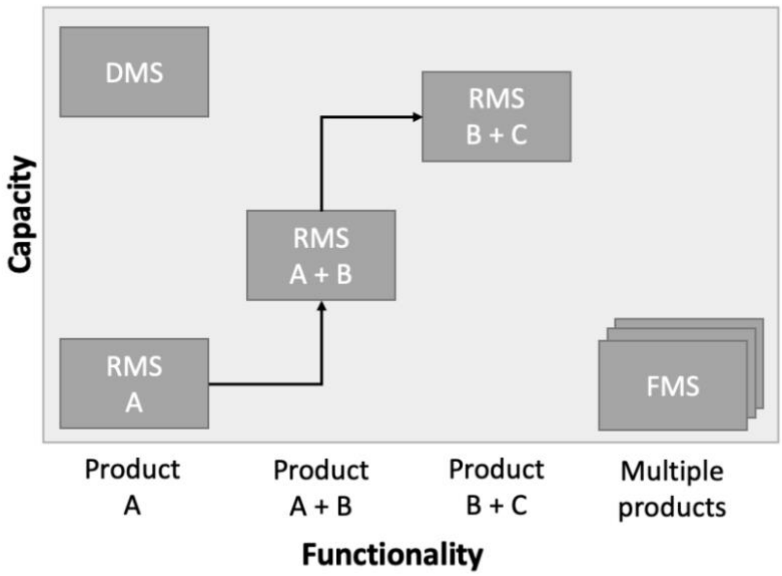

Figure 2 - DMS, FMS and RMS, adapted from Koren (2006).

RMS has further been presented as the hybrid system between DMS and FMS. This since RMS brings together the benefits of having cost-effectiveness as a result of mass production and responsiveness to change in features of the products within a product family (Koren & Shpitalni, 2010).

2.1.1 RMS classification

The competitiveness among industrial companies puts pressure on manufacturers to stay viable and respond to customer demands. This in turn creates the necessity to frequently introduce new products in existing production systems (Bellgran & Säfsten, 2009). Many researchers have associated the development or change of the production system to match product introductions, particularly RMS. For instance, Säfsten & Aresu (2000) conducted a survey on 15 companies. In the research, Säfsten & Aresu (2000) linked introducing new products to the changes in assembly lines that give the companies the advantage of launching new products before their competitors. Also, Surbier (2014) emphasized on the relation between production ramp-up for new products and disturbances in product quality and assembly line performance. Both studies can connect to the works of ElMaraghy (2006) and Koren & Shpitalni (2010) on reconfigurability enablers. ElMaraghy (2006) identified two types of flexibility: physical and logical. The physical aspect includes production layout, machines, and material handling equipment, while the logical aspect includes for instance, production planning, human resources, and rerouting (Figure 3).

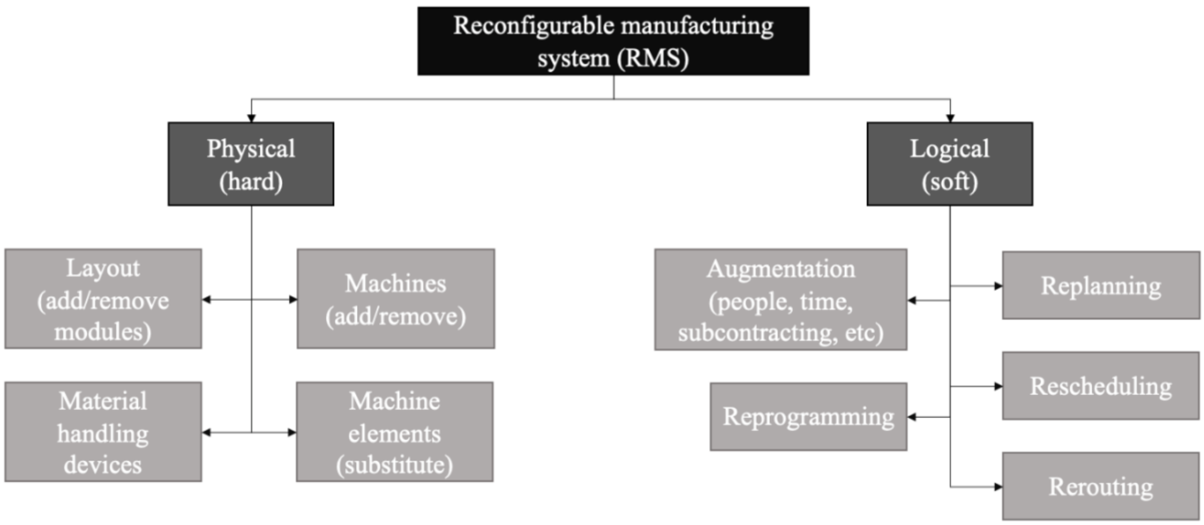

Figure 3 - RMS soft and hard classification, based on ElMaraghy (2006).

Considering the abovementioned classifications, RMS can be supported through both physical and logical aspects. For example, scaling up the production capacity can be achieved by adding more machines to an existing production system. However, changing production planning or product mix can lead to an increase in the volume without changing the physical structure of the production system (ElMaraghy, 2006; Lohse et al., 2006; Mehrabi et al., 2000). Furthermore, Wiendahl et al. (2007) argue that soft reconfigurability can be valuable to increase cost efficiency and respond to the demand without investing in the new line features.

2.1.2 RMS characteristics

Researchers have identified seven characteristics that enable the manufacturing system to achieve reconfigurability, these are presented in Table 1 below based on (Koren et al., 1999; Koren & Shpitalni, 2010; Maler-Speredelozzi et al., 2003; Naor et al., 2010; Rösiö et al., 2019; Wiendahl et al., 2007; Youssef & Elmaraghy, 2006). However, it is important to note that researchers have identified RMS characteristics using different terms. For example, Wiendahl et al. (2007) found mobility to be one of RMS characteristics , while Napoleone et al. (2018) and Rösiö et al. (2019) did not acknowledge the term mobility but instead covered mobility within other characteristics, namely as modularity and integrability.

Table 1 - RMS characteristics

Characteristic	Definition
Scalability	Scalability of the system's production rate is required to respond to changes in demand in a timely manner. Scalability encompasses both system scalability and capacity scalability. The former, i.e., system scalability, refers to meeting market demand with the least amount of system capacity growth. Capability flexibility, on the other hand, has two components. One of these components is the physical flexibility of attaching and disconnecting machines and material handling equipment to the production system. The other component is logical flexibility and refers to the ability to extend production time and increasing working shifts or manpower.
Customization	The ability of a production system to respond to differences within the same product family is referred to as customization. It is possible to use the same software to create different features within the same product family using a customized configuration. To allow system customization, there is also a need for software to track running mixed products within the same line.
Convertibility	Convertibility refers to a manufacturing system's ability to convert between various configurations in order to meet fluctuating demand. When switching between product variants and future models, a convertible development system requires the least amount of setup time.
Modularity	Production system modularity refers to the standardization of system components and functions. Modularity allows for the replacement, removal, and addition of modules without disrupting other components of the system. Modularity enables the construction of complex systems that can react to changes in product features or fluctuating demand.
Integrability	Production system integrability, also known as compatibility, refers to the compatibility of various applications, materials, and interfaces within the various components of a production system. Integrability is critical for ensuring coordination between all production system components at various stages of production. When a new component is added to an existing system, it is critical to connect it logically and physically to the current control system and production infrastructures. On a physical basis, integrability enables newly connected components to send and receive goods and materials with ease. Physical integrability involves exchanging data and control signals with other elements of the production system, while logical integrability entails exchanging data and control signals with other parts of the production process.
Diagnosability	Diagnosability enables the manufacturing system to diagnose performance disturbances rapidly and accurately within the production system. The system must quickly diagnose equipment and material handling errors and assess their effect on the rest of the system. Furthermore, diagnosability in manufacturing systems entails tracing product quality issues and investigating root causes.
Mobility	The freedom to transfer production system elements is referred to as mobility in the RMS. This covers machines, facilities, and infrastructure. Mobility contributes to the system's flexibility; unrestricted equipment can be quickly transported within the factory to expand production capacity wherever there is a lack of production resources.

In an attempt to break down reconfigurability characteristics on a more detailed level, Rösiö et al. (2019) presented a total of 37 assessment criteria connected to the seven characteristics of RMS (see Table 2 below).

Table 2 - RMS sub-characteristics and descriptions, adapted from Rösiö et al. (2019).

Characteristic	Sub-characteristics	Description
Scalability	Machinery	The possibility to add or remove machinery within the production system.
	Shifts and workers	The possibility to vary the number of shifts and workers in the production system.
	Lead time	The possibility to increase volume capacity by reducing lead time.
	Line balancing	The ability to rearrange resources and improve workload distribution across workstations.
	Task time	The possibility to vary task times in manual assembly operations.
	Utilization of space	The possibility to vary space utilization.
Customization	Tool customization	The possibility to use same tools for different product variants (within the same product family).
	Controller customization	Ability to integrate controllers (e.g. programmable logic controllers) into the general controller platform.
	Operation/Machine customization	Ability to operate several tasks within the same machine.
	System customization	Ability to upgrade and adapt the current production system to handle future product variants.
	Size customization	Ability to design the product based on available dimensional space
	Colour customization	Ability to alter the products' visual appearance.
	Design customization	Ability to customize the products' design according to customer demand.
Convertibility	Software convertibility	Ability to reprogram the existing production software.
	Increment of conversion	Ability to produce new product variant jointly with existing product variants in the same production line.
	Routing convertibility	The capability of restructuring and reorganizing Automated Guided Vehicles (AGVs).
	Replicated machines	Possibility to investigate the availability of replicated machines which can be changed without changeover.
	Fixture convertibility	Capability to alter fixtures in order to fit them to all variants in the product family, with minimum switching time.
	Tool convertibility	Potential to alter tools automatically or with minimum switching time.
	Multidirectional	Ability to include material handling devices which are multidirectional.
	Asynchronous motion	Ability to include material handling devices which have asynchronous motion.
	Level of automation	Ability to include a high level of automation in the production system.
Modularity	Tool modularity	Capability of altering tools without affecting appurtenant machines.
	Workstation modularity	Capability to easily altering workstations without affecting appurtenant machines.
	Fixture modularity	Capability to changing fixtures without affecting appurtenant machines.
	Operation sequence	Ability to structure operation sequence to fit all variants within the same product family.
	Component sharing	Possibility of sharing modules consisting of basic components to create different variants across product families.
	Component swapping	Possibility of pairing two or more modules to a basic component to create different variants within a product family.
	Cut to fit	Possibility of changing the dimensions of a module in order to match another module.

	Bus modularity	Possibility to match disparate modules to a basic component.
Integrability	Tool integrability	Capability to integrate new tools in existing machines in the production system.
	Control software	Capability to integrate already existing control software into new tools and machines.
	Information handling integrability	Capability to integrate information with new work tasks in the production system.
Diagnosability	Poka yoke	The capability to detect the usage of correct tool and components for the product family variants.
	Information board	The ability to display the upcoming operation on the focal machine or assembly line.
	Traceability	The ability to trace the product's current production stage/operation.
	Quality assurance	The ability to immediately detect unsatisfactory product quality through visual technology (e.g. cameras and sensors).

2.1.3 RMS characteristics and improvement levels

As a way of explaining the relationship between RMS characteristics and the system's lifecycle, Napoleone et al. (2018) present a framework approach, as illustrated in Figure 4 below. According to Napoleone et al. (2018) there is a logical relationship connecting the RMS characteristics. For instance, the characteristics modularity and integrability are required on a lower level than their dependent characteristics, i.e. diagnosability, scalability, convertibility and customization. The latter is, compared to the other characteristic, a strategic perspective. It has the capability to create a possibility to either proactively or reactively implement reconfigurability. Due to this ability, customization is recognized as having a final connection to all other RMS characteristics (Napoleone et al., 2018).

Napoleone et al. (2018) are also arguing that RMS characteristics can be further divided into three classes, which is based on their correlation in the system lifecycle. The classes regard configuration, reconfiguration, and change-driver/change-driven characteristics. Whereas for instance, the characteristics scalability and convertibility are associated with the reconfiguration characteristics. This since they are essential for achieving capacity or functionality changes in the production system (Napoleone et al., 2018). Hence scalability and convertibility are recognized as being a part of the period typified when making decisions regarding system changes, in other words, the reconfiguration period (Napoleone et al., 2018; Rösiö, 2012).

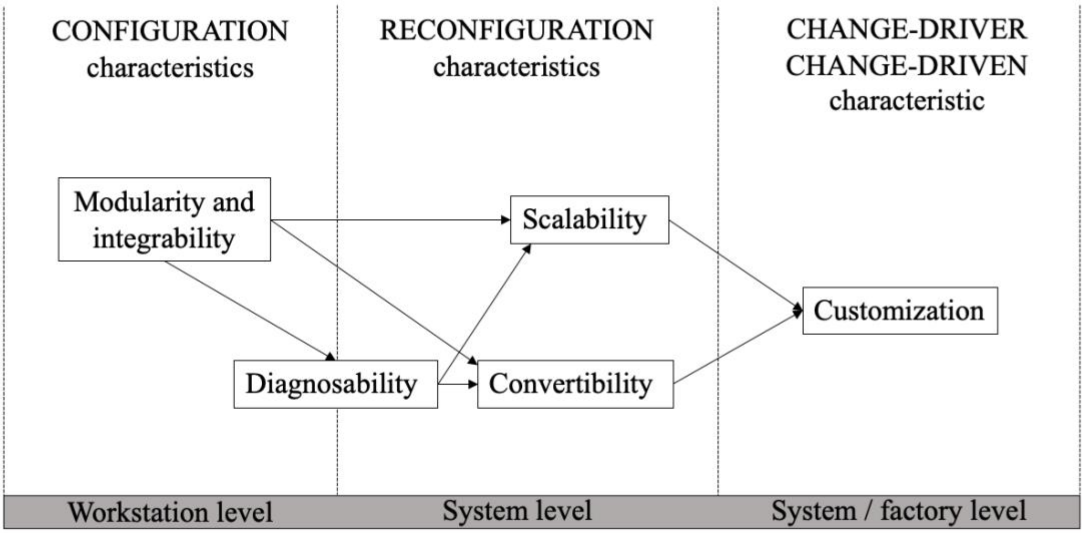

Figure 4 - Reconfigurability in assembly production, based on Napoleone et al. (2018).

Napoleone et al. (2018) also describe that the lowest level to find the RMS characteristics modularity, integrability and diagnosability is on an assembly station level. Due to the position of these characteristics being at a workstation level (e.g. assembly station), i.e. the most concrete level, the characteristics convertibility and scalability are at the possible to achieve on a system level (e.g. cells, production lines or assembly systems). This enables a possibility to achieve customization on both system and factory levels (Napoleone et al., 2018).

2.2 Single-, mixed- & multi-model assembly lines

Assembly lines were famously introduced by Henry Ford in the beginning of the twentieth century. Assembly lines are setups for manufacturing processes where value is added to products, for instance in terms of operations performed or subparts added. Traditionally, workstations where these operations occur are logically placed in a predetermined sequence and placed in proximity to each other. However, conveyor belts or similar transportation systems are also solutions frequently used when necessary. At the workstations, humans or machines are to perform a predetermined set of operations which they complete before the product is transported to the subsequent workstation (Fortuny-Santos et al., 2020). Since assembly lines can be comprised of machines, tools and human labour, while being quite extensive, they are associated with a high level of investment costs (Alghazi & Kurz, 2018; Fortuny-Santos et al., 2020). This puts an emphasis for companies on establishing a proper configuration of assembly lines (Alghazi & Kurz, 2018).

Originally, assembly lines were implemented as a means for companies to accomplish mass production of identic products while staying cost-efficient (Alghazi & Kurz, 2018; Fortuny-Santos et al., 2020). However, in line with organisational and technological development, assembly lines have developed and nowadays several products can be assembled in the same assembly line (Fortuny-Santos et al., 2020). The configurations of product and assembly lines can be divided into three main categories; single-model assembly lines, mixed-model assembly lines and single-model assembly lines (see Figure 5 below) (Güden & Meral, 2016; Olhager, 2013; Şeker et al., 2013).

Single-model assembly lines are the least complex assembly line. These are commonly implemented in mass production facilities. Primarily since they traditionally enable the possibility of having operators with little training to manually assemble complex and detailed products (Cevikcan et al., 2009).

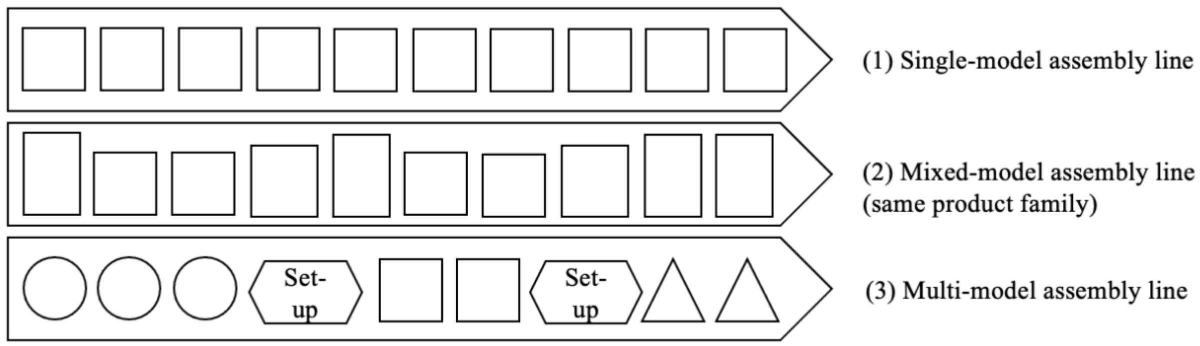

Figure 5 - Different assembly lines types, adapted from Olhager (2013).

Mixed-model assembly lines (MMALs), on the other hand, are used to manufacture several products within the same product family (Akpinar et al., 2017; Olhager, 2013). These are simultaneously assembled on the same line (Mirzapour Al-E-Hashem et al., 2009). In MMALs, each specific product variant has its own task precedence rules, which are combined into a precedence diagram of the entire product family (Akpinar et al., 2017). MMALs are frequently used in car-manufacturing facilities as these tend only to produce a limited fixed set of product families. Normally, these do not require any machine- or tool setup between different product variants. However, there is a higher level of complexity in material- and component handling in MMALs as they need to serve the needs of several models simultaneously (Olhager, 2013).

The third category of assembly lines is multi-model assembly lines. If the products assembled in the production line are of comprehensive difference, setup time might be required between producing the products in sequence. Thus, the key question when producing in multi-model assembly lines regards whether the products have a sufficient similarity level in terms of components and production resources in order to be economically beneficial (Olhager, 2013).

2.3 Line balancing problems

Assembly lines were initially intended to produce a limited variety of products in large quantities. A setup like this allows low production costs, short cycle times, and high quality. However, due to the high capital cost needed to build and operate an assembly line, manufacturers produce one product with various features or several products within the same product family on a single assembly line simultaneously (Bellgran & Säfsten, 2009). Producing or assembling of a product often requires several operations. Seldom are these operations unidentical and require various time for completion, a workload varies among employees and stations due to the different operating times. As a result, the aim is to delegate the same workload to all employees or computers. To provide a smooth work distribution within assembly lines, two aspects need to be considered: 1) The total number of workstations must be kept to the minimum, 2) The logical precedence constraints that must be followed. The latter aspect is required since some of the processes cannot be performed before their predecessors (Groover, 2016; Watanabe et al., 1995). Furthermore, there is a set of assumptions that need to be considered in solving assembly line balancing problems (ALBP), the assumptions decide the input data, techniques, and the final solutions for the problem. Although the final goal for all ALBP is to reach a feasible work distribution, the method is different based on the line characteristics, such as the number of products per line, the pre-determined number of workstations, or task time (Battaïa & Dolgui, 2013).

When deciding which strategy to use to solve ALBP, some assumptions about the assembly line must be considered. As an example, assumptions on the number of models to be manufactured are referred to as single assembly line balancing problems (SALBP) in the case of a single model product, while mixed-model assembly line balancing problems (MMALBP) are problems with two or more products produced on the same line (Mirzapour Al-E-Hashem et al., 2009).

Another assumption to note is the objective of the balancing, whether it is to minimize the number of stations or to increase throughput by reducing the cycle times of the assembly activities. Thus, ALBP type I aims to reduce the number of stations or staff needed to meet the output demand where the process time is set. ALBP Type II, on the other hand, aims for the maximum output rate and the shortest cycle time while maintaining a constant number of workstations. Regardless of the distinction between the two, both assume that the operating time allotted to stations does not exceed the cycle time of the assembly line (Becker & Scholl, 2006; Rabbani et al., 2016).

However, these assumptions are not separated, see Figure 6, and it is critical to consider all of the assembly line constraints and objectives when agreeing on the best strategy. This since assembly line balancing is by definition strategic. When confronted with such a challenge, planners often strive for a decision that will have a long-term productive effect (Xu & Xiao, 2009).

	Assembly line balancing problem Type I	Assembly line balancing problem Type II
Single assembly line balancing problem (SALBP)	SALPB Type I	SALPB Type II
Mixed-model assembly line balancing problem (MMALBP)	MMALPB Type I	MMALPB Type II

Figure 6 - Assembly line balancing problems' assumptions and constraints

2.4 Decision-making tools in line balancing

Today's decision-makers need to frequently make important decisions in a highly competitive environment. The need to evaluate various alternatives has become even more complicated in recent decades, leading to an increased use of digital spreadsheets as a support tool for making more accurate decisions. This primarily since they are a workable solution for many users, especially in management and operations research applications (Caine & Robson, 1993; O'Donnell, 2001). The process structure described by Ragsdale (2008) for decision-making can briefly be described in three steps. The first step involves identifying decision variables representing the quantities that the user can control and changing the model's outputs. The second step covers identifying model constraints that include the acceptable values for decision variables. The final step involves identifying the desired model objectives. For instance, objectives can include a predetermined maximum or minimum value, or a decision which guarantees a result within a certain range. Several researchers have described different ways to create decision-making models in Microsoft Excel (Caine & Robson, 1993; Coles & Rowley, 1996; Nogoud et al., 2017; Ragsdale, 2008). Even though these models might be differently structured, they all followed similar steps with only minor differences. These steps have been identified as:

1) Understand the problem variables in order to organize the data for the model in the spreadsheets. The relation between data and dependences decides both the data entry and output requirements.
2) Replace the spreadsheet's cells to corresponding decision variables and use labels to explain the meaning of every set of data.
3) Establish the formulas that link the cells in order to achieve the objective of coping with model constraints.
4) Validate the model's ability, accuracy, and usability. Validation of the model using unexpected data such as negative numbers or unexpected data can examine the model's robustness. Also, by using simple data with known results, it is possible to test if the model delivers expected outputs.
5) Document the model procedure and provide clear guidelines for the user. These should include, but be limited to, labeling the data and equations used, drawing a spreadsheet

map, and clarifying the formulas.

6) Implement the model and receive early feedback from the users to optimize the model in order to reach the desirable results.

2.5 Line balancing models and computation

Microsoft Excel spreadsheets have been the most widely used tools in recent decades when it comes to operation analysis and solving project management network problems (Caine & Robson, 1993). Ragsdale and Brown (2004) created one of the first models which use Microsoft Excel spreadsheets to explain and solve predecessor relations between tasks. About a decade later, both Weiss (2013) and Wellington & Lewis (2018) extended the previous work in a new area of application through the use of a heuristic approach to solve line balancing problems for a single model product. Their work shares the same basic structure, which can be divided into two major steps. The first step regards identifying the assembly line parameters in the form of a table. This table includes inserting the values of task names, task times (operations time), required cycle time (operations time) and immediate predecessors between tasks (Weiss, 2013; Wellington & Lewis, 2018).

The second step is to identify the workstations' feasibility based on two requirements. Firstly, all previous operations have been assigned to the available stations. Secondly, the sum of task times is less than or equal to the theoretical maximum time required to produce one product through the assembly line. Following that, the task is allocated in accordance with the existing priority rule. For every iteration, a single task is considered at a time. The computation of the process is achieved through combinations of built-in functions in Microsoft Excel. The coding system is structured in such a way that it automatically allocates tasks to stations by assigning 0 for tasks which have not been assigned yet, and -1 to tasks which have been assigned to previous stations. This allows the spreadsheet to identify the first task to start with it and to stop the computation when no more task is available. The spreadsheet checks if the activity code is 0 and then checks if the available time in the station is less than the operating time using the built-in Microsoft Excel IF functions. In the case when all conditions are met, the sheet subtracts the task (operation) time from the station time and keeps the remaining time to be set as the current overall available time. Thereafter the sheet changes the code of the task to be -1 or less. Once this has been accomplished, a new iteration starts by checking if the next task code is equal to 0. (Weiss, 2013; Wellington & Lewis, 2018). Some common Microsoft Excel formulas frequently used by Caine & Robson (1993), Ragsdale & Brown (2004) and Wellington & Lewis (2018) are:

- *IF*: check the logical conditions for a priority rule and station availability through the mathematical denotations "<" ">" "=".
- *SUM*: at each iteration, the *SUM*-function is used to count the number of tasks that fulfil the requirement and thereafter returns the task code for the new iteration.
- *SEARCH*: maintain the task code with a combination of IF conditional functions.
- *VLOOKUP*: searches for a certain task name and time with the task code in the inputs.
- *OFFSET*: used for dynamic functions where there is a need to return a value based on a reference cell. The *OFFSET*-function is used in order for tasks to be assigned based on the line balancing priority rules.

2.6 Key performance indicators in line balancing

A key performance indicator (KPI) is defined as a comparable value or number which is used to gain insight into a certain performance. The KPI can be compared to either a selected internal target or an external target. The number or value in the KPI consists of either collected or calculated data (Ahmad & Dhafr, 2002). In regard to assembly lines, there are two main types of KPIs. These differ based upon time perspective. The KPIs which are reporting an assembly line’s current status and performance is referred to as online KPIs. Operators and managers frequently use these to ease decision-making regarding assembly line improvements or problems in need of instantaneous alteration. On the other side of the time perspective, offline KPIs are indicators of an assembly line’s performance calculated or collected based on historical data. Hence offline KPIs are more frequently used by managers when the aim is to proactively identify problems in the assembly lines and thereby enable the possibility of constructing action plans to avoid the identified problems in the future (Mohammed & Bilal, 2019).

Hitherto, many authors have tried to solve the issues in line balancing. Both regarding the simple assembly line balancing problems or more complicated assembly line which produces multiple products within the same line, for instance McMullen & Tarasewich (2003), Su et al. (2014) and Samouei (2019). With this, new algorithms and techniques have been developed. Consequently, the usage of KPIs has also been developed. When Salveson (1955) first introduced line balancing, the KPIs used were cycle time, throughput time, idle time, machine utilization and balancing loss. Nowadays the KPIs tend to be more advanced, for instance taking shape in the form of flexibility of staff, process planning, market requirements (März, 2012) and planned order execution time (Ferrer et al., 2018).

2.7 Assembly line investment costs

Investments, for instance regarding production and assembly line, is a critical factor of a company's long-term economic performance. Once a decision has been made, it is seldom possible to reverse the actions taken (Nickell, 1978). However, many organisations, both within the public and private sectors, still base their investment on the initial purchase costs, without any consideration of the assets’ life span and discount rate. In order to cope with these factors, and thus facilitate a more realistic financial outcome, investment calculation methods such as Life Cycle Cost (LCC) techniques and calculations have been developed (Woodward, 1997). LCC techniques are particularly widespread as they optimize the total cost of ownership by taking a wide range of technical data into consideration (Tosatti, 2006; Woodward, 1997)

Similar to the principle of LCC calculations, the Net Present Value (NPV) method is also taking the discounting cash flows over a certain time-line into consideration in the investment decision. Although, in contrast, NPV is typically used in business planning and for making strategic decisions. In contrast, LCC techniques on the other hand are intended for enabling a comparison of the anticipated economic lifecycle performance of investment alternatives, for instance regarding production systems (Tosatti, 2006; Woodward, 1997).

2.8 Monte Carlo simulations

The Monte Carlo simulation method’s origin dates back to the 1940s (Platon & Constantinescu, 2014). However, it was not until 40 years later when Monte Carlo simulations started receiving concentrated attention from academia (Kelliher & Mahoney, 2000). Since then, they have been used by professionals in a wide arrange of settings, for instance, in finance, project management and production (Khalfi & Ourbih-Tari, 2020; Wang, 2012). The Monte Carlo method is a computerized simulation technique which allows the user to analyze the entire range of possible outcomes and the impact of existing risks and uncertainties. Hence, the user is able to identify key insights regarding the relationship between inputs and outcomes and thus enable better decision making when uncertainty is present (Kelliher & Mahoney, 2000; Khalfi & Ourbih-Tari, 2020; Saipe, 1977). Monte Carlo simulations are primarily useful since they are easy to perform, but also due to their ability to provide the user with the possibility of running thousands of iterations very quickly. (Kelliher & Mahoney, 2000; Platon & Constantinescu, 2014).

As aforementioned, Monte Carlo simulations are useful in many situations, none the least in investment calculations. This since the key difference between Monte Carlo simulations and other modeling techniques is their ability to not require certainty or normality in the inputs (Kelliher & Mahoney, 2000), which is a frequent issue in investment decision making (Platon & Constantinescu, 2014). In investments, Monte Carlo simulations can be used to calculate possible outcomes when uncertainty in input values has a great impact on the final results (Kelliher & Mahoney, 2000). According to Platon and Constantinescua (2014), one of the most interesting research on Monte Carlo simulations was conducted by Dienemann in 1966 and regarded cost estimating the uncertainty of investment projects. In more recent days, Monte Carlo simulation to calculate investment decisions with an intrinsic uncertainty has been, for instance, tested by Hacura et al. (2001). In their research, they used investment expenditures connected to purchasing a new production facility, including building costs, technical equipment, assembly work, and current assets (Hacura et al., 2001). Which showed how the performance is influenced by the variation of certain cost and demand scenarios (Renna, 2017). Furthermore, the number of iterations required to run Monte Carlo simulations is significant in order to get viable results. Hauck & Anderson (1984) argued that the majority of studies on Monte Carlo simulations have chosen to run between 500 and 1000 iterations. This argumentation corresponds to, for instance, Caralis et al. (2014), who run several Monte Carlo simulations in their research, whereas the most extensive consisted of 1000 iterations.

3 Methodology

The third chapter covers the methodology, beginning with explaining the research design. Afterward follows a description regarding the usage of literature studies, case study, interviews, document analysis and focus group in the thesis. Thereafter, the model validation procedure is presented. Lastly, the trustworthiness, ethical- and moral perspective is declared for.

3.1 Research design

The thesis purpose was to "*Develop a decision-making tool which fit in a RMS milieu used to identify whether to introduce and produce a new product into an already existing assembly line or to invest in a new assembly line"*. Given the purpose, the nature of the thesis is equivalent to exploring and explaining. These attributes correspond to a qualitative research approach (Leedy et al., 2019). The qualitative approach is namely characterized as having flexible guidelines which were necessary since the outcomes were not predetermined, but instead explorative. Also, the data necessary to answer the research questions was collected in a small sample and through, for instance, non-standardized interviews and document studies, which corresponds well to the natural characteristics of a qualitative approach (Leedy et al., 2019).

In order to fulfil the purpose, four research questions was created. RQ1 and RQ2 were necessary to answer in order to create the theoretical foundation for creating the decision-making tool. Whilst in RQ3 the theoretical knowledge was combined with empirical data and thus enabled the possibility to secure the applicability of the decision-making tool in an industry setting. In order to validate the decision-making tool from an RMS perspective, and thereby illustrate how the decision-making tool is supporting RMS, RQ4 was created. The connections between research questions and methods used are depicted in Figure 7.

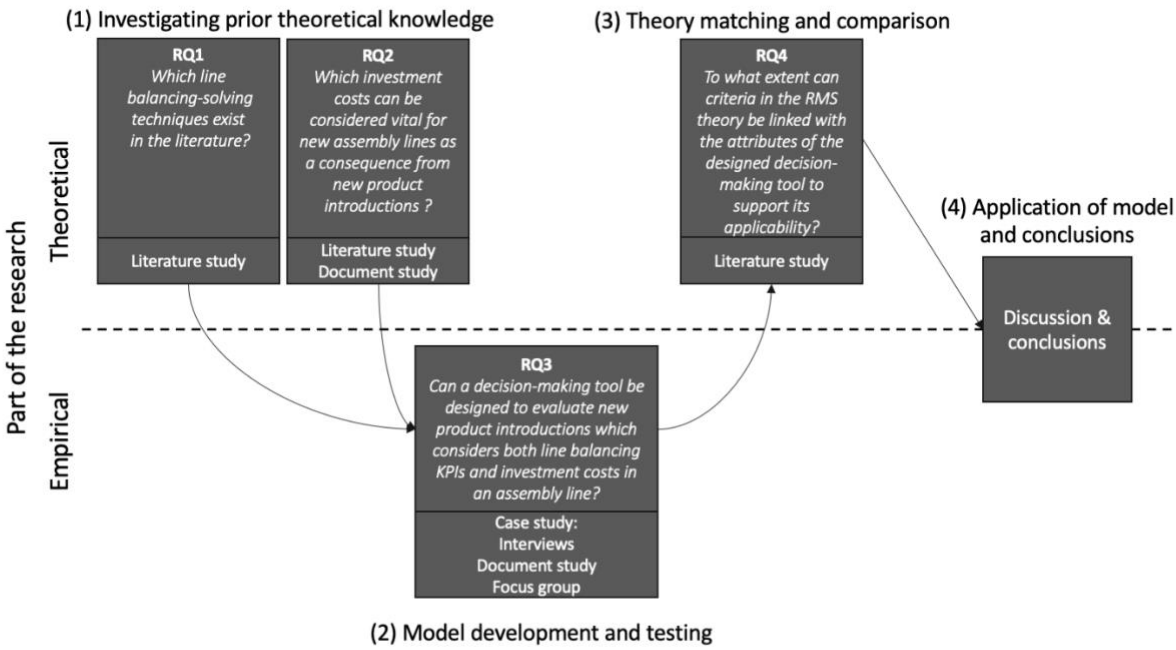

Figure 7 - Research design, adapted from Kovács & Spens (2005).

3.2 Literature studies

Since this thesis is covering a topic which thus far has been overlooked by academia, the need to create a theoretical foundation for the DMT to stand upon is crucial. Therefore, several extensive literature studies have been conducted. The literature studies have been structured to focus on certain topics, these regarded RMS, line balancing, and assembly line investment costs. By doing this, sufficient knowledge regarding the topics to create and evaluate the DMT was gained. The literature studies took place in the shape of systematic reviews. This due to the fact that a systematic review is appropriate to use when the goal is to draw a conclusion regarding what is both known and unknown within a particular topic (Denyer & Tranfield, 2009; Saunders et al., 2016). This is corresponding well to the limited research previously conducted on RMS and line balancing, as seen in Table 3 below. Besides, the systematic literature review also has an increased internal validity due to its ability to minimize potential biases such as selection bias and publication bias. The former regards researchers tend to choose articles which correlate with his or her existing belief (Booth et al., 2016). The latter occurs when, for instance, reviewers or editors act indifferently dependent on the direction or strength of the focal article's findings (Booth et al., 2016; Gilbody & Song, 2000).

The literature studies were carried out through a five-step process, inspired by Booth et al. (2016). The process is depicted in Figure 8 below. All searches were carried out in the abstract and citation database Scopus. The initial searches were based on carefully selected combinations of keywords. In order to exclude non-relevant papers, search filters were used. The filters primarily involved limiting the searches to papers written in English and excluding non-relevant fields such as environmental science, physics, and chemical engineering. The filters also included limiting the searches to document types such as articles, books, and conference papers. Once the filters were applied, the process was initiated with the first reading round, where the abstract was read, and the papers reckoned relevant were selected. The second reading round incorporated quickly reading the papers, and thereafter selecting the most relevant papers to the third and final selection round. This round included reading the articles once more in detail, while taking notes, excerpting quotes, and highlighting relevant findings.

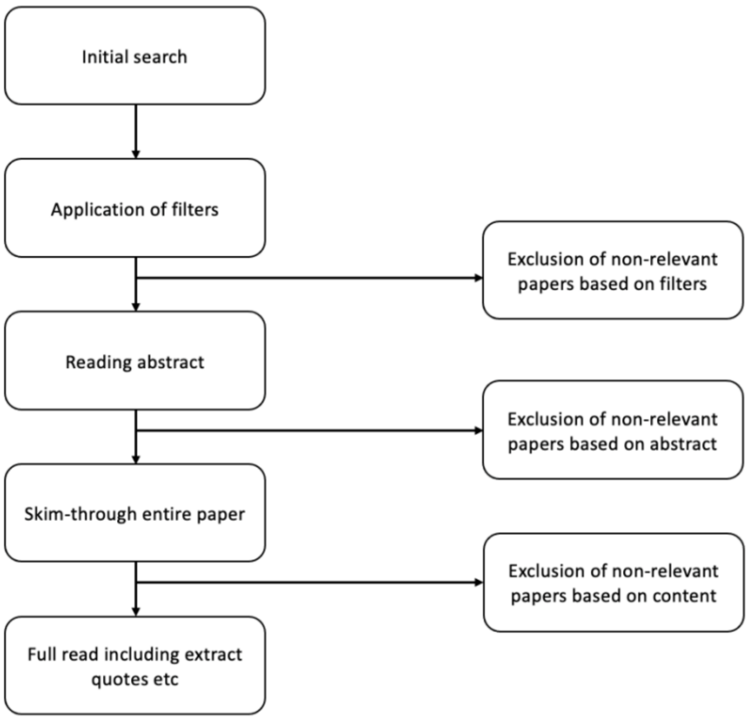

Figure 8 - The applied process for the literature studies

In total, three literature studies were conducted. One of the literature studies covered the hitherto conducted research on RMS and line balancing. This literature study was performed with the aim of gaining full insight into the current research on RMS and line balancing. In particular how other researchers have adapted line balancing tools to fit RMS. However, as seen in Table 3 below, the hits of searching for RMS and Line balancing were very few, proving the limited research within the areas. This literature study also covered searching for typical characteristics related to RMS, as a way of enabling the possibility to test the correlation between RMS and the developed decision-making tool.

A literature study covering line balancing was also conducted. This was performed to create a theoretical foundation for the thesis, as well as finding possible line balancing techniques and algorithms necessary to create the decision-making tool. Even though there might be a clear knowledge gap about the application of line balancing in RMS, as aforementioned, the need to identify which line balancing techniques that can be used in RMS was necessary. A numerous amount of algorithms and techniques were identified, however, the majority of these were either too complicated to apply in a wider industry setting, or too mathematically complex to transfer into a Microsoft Excel file.

Lastly, a literature study focusing on assembly line investment costs was conducted. By identifying investment costs frequently used when estimating costs for new product introductions, the authors were able to design the decision-making tool with the possibility of including these in mind. As seen in Table 3, the initial search for assembly line investment costs only resulted in a single hit, which forced broader searches within the field.

Table 3 - Applied keywords and search results in the literature studies

Theoretical topic	Keywords	Hits	Incl. filters
RMS	"Reconfigurable manufacturing system*" AND ("Characteristic*" OR "Criteria*" OR "Driver*" OR "Enabler*")	215	177
	"Reconfigurable manufacturing system" OR "RMS" AND "Line balancing"	10	9
	"Reconfigurable manufacturing system*" OR "RMS" AND "Mixed-model assembly line*"	4	4
Line balancing	"Mixed model assembly line balancing"	140	118
	"Mixed-model assembly lines" AND "Line balancing"	241	192
	"Multi-model assembly line*"	32	29
	"Line balancing" AND Algorithm*	1229	234
	"Line balancing" AND Technique*	373	117
	"Line balancing" AND "Decision making tool"	2	2
Assembly line investment costs	"Assembly line*" AND Investment* AND ("New product introduction*" OR NPI)	1	1
	"Assembly line*" AND Investment*	214	156
	Investment* AND Costs* AND Calculation* AND (Production OR Manufacturing)	607	212

3.3 Case study

The aim of this research was to develop a decision-making tool which provides companies with the possibility to scientifically calculate whether it is economically beneficial to produce the new product in an already existing assembly line, or to invest in a completely new assembly line. Hence, ensuring the industrial application of the tool is crucial for the research's relevance. In order to achieve this, a single case study was conducted. The case study method was chosen since it is an empirical method that is used when investigating an in-depth and realistic case (Yin, 2018), thus making it a suitable choice for developing, testing and validating the DMT. Also, by conducting the case study in parallel to designing the decision-making tool, the possibility of continuously validating the DMT’s industrial application existed.

Nevertheless, there are a few downsides with using case studies. For instance, case studies seldom have a distinct purpose. If studies have stated a clear purpose, then the problem instead frequently relates to authors not being able to describe how the purpose is addressed in the study (Corcoran et al., 2004). In order to deal with these issues, the purpose has been well-defined, and research questions have been formulated carefully to support the purpose. Another downside of case studies is that they require data from multiple sources. Therefore, the collected data needs to be congregated through triangulation (Yin, 2018). This has been accomplished by using three different data collecting methods in the case study: interviews, document analysis and focus group. Below follows a detailed explanation of how these methods have been utilized.

3.3.1 Interviews

In case studies, the interview method is one of the most significant information sources (Tellis, 1997; Williamson, 2002), hence it was used in this study. The interviews took place in the form of bi-weekly meetings with a production engineer at the case company. Since the focus of the interviews was to gain information about certain areas and topics, rather than about the respondent, the interview was a viable method (Alvesson, 2011). According to Patel & Davidson (2011), interviews can take place in different styles, primarily depending on their structure and level of standardization. The interviews in this research were conducted as discussions, whereas solely a few questions and the to be discussed topic was prepared beforehand. These discussions, characterized by a low level of standardization and structure, corresponds to unstructured interviews, as described by Patel & Davidson (2011). Performing unstructured interviews was chosen as they are typically used when aiming to gain a deeper understanding of a topic which a certain person possesses (Patel & Davidson, 2011). The information retrieved from the interviews was in turn used to develop the decision-making tool.

3.3.2 Document studies

Document studies were carried out through the process of extracting data and information from existing documents, and thus enabling the possibility to design, test and validate the decision-making tool from an industry point of view. Document studies were chosen since they are an adequate complement to other methods, for instance, literature studies and interviews (Skärvad & Lindahl, 2016). In total, two document studies were performed, and a total of 6 documents were reviewed. For both studies, the documents were sent via e-mail by a production engineer at the case company (see Table 4). The authors were thus able to study the documents in their own pace, potentially increasing the likelihood of properly understanding the data. This was crucial since it is significant to interpret internal documents carefully in document studies. The significance stems from the existing probability that the company has altered certain data, and thus is not fully representative of the actual current state (Yin, 2018). Also, to further minimize this risk of misreading data, interviews were carried out after performing the document studies. These incorporated the company representative explaining the general content of the documents, as well as answering questions for clarification.

Table 4 - Documents studied

Date received	Document description	Source
21st January 2021	Current staffing and balancing procedure	Production engineer
21st January 2021	Detailed information of two products to be tested in the decision-making tool	Production engineer
1st March 2021	LCC analysis template	Production engineer
1st March 2021	LCC analysis – assembly update case	Production engineer
1st March 2021	Business case calculation model template	Production engineer
1st March 2021	Business case calculation model - assembly update case	Production engineer

The first document study involved studying documents, in the shape of Microsoft Excel files, and regarded the case company's current way of doing line balancing. By doing this, a profound understanding of the level of complexity and necessary inputs and outputs of the decision-making tool was gained. Because, in order to ensure the decision-making tool's applicability, the level of complexity must be adjusted to match the general knowledge within the industry, otherwise the tool risked getting viewed as solely academically usable. The second document study regarded investment calculations. It consisted of studying several Microsoft Excel files showing how the case company is calculating investments. The main focus was to study which fixed costs are taken into consideration when simulating and calculating investments. The insights gained were used to develop the investment calculations of the decision-making tool, as described more in detail in the forthcoming chapter.

3.3.3 Focus group

As a way of collecting extensive feedback from the case company, a focus group was set up and carried out. By doing this, it was possible to gain insights into the decision-making tool's complexity, usability, and generalizability. The focus group method was selected in particular due to its ability to enable a fixed set of individuals to provide feedback and opinions in a benign setting (Greenbaum, 2000). In total, four employees from the case company participated in the focus group. Choosing participants is a crucial step to facilitate focus group, because one of the most common mistakes made in the focus group process is to select inappropriate participants (Greenbaum, 2000). Hence, the participants partaking in the focus groups were carefully selected. To ensure the collection of feedback for both the line balancing and production investment costs modules in the DMT, the participants were chosen based on their occupation, knowledge, and experience within these fields. Employees from departments responsible for both assembly line balancing and production investment cost estimations were therefore selected for the focus group. The DMT was sent to the participants approximately two weeks prior to the occasion. By doing this, the participants were able to investigate the DMT before the occasion, and thus also fully grasp the DMT's functions. The focus group occasion took place digitally, as the ongoing Covid-19 pandemic prohibited the participants from being gathered at the same place.

In total, the focus group occasion lasted for two hours and followed a structure inspired by Krueger & Casey (2009). The structure focused around a pre-made questioning route which consisted of five major parts; opening questions, introductory questions, transition questions, key questions and ending questions (Krueger & Casey, 2009). The structure enabled the possibility to facilitate a discussion amongst the participants, as well as ensuring that all necessary areas were covered in order to gather complete feedback on the decision-making tool.

3.4 Case company context

The case company's current product industrialization process starts with a product design, after which the product features and requirements are developed and submitted to production planning personnel. During this stage, the data available from the data management system is used as an input for AVIX software to conduct time studies and calculate the process time required to perform all assembly activities. During the assembly planning, current assembly lines are used as guides to measure the movement times required to complete the assembly task, as well as the setup time needed to change the line setup to receive the new product variant's task times. Based on previous experience and estimations from assembly planning employees, this data is used to create line balancing using one of the line balancing techniques. However, these estimates are not precise since they are dependent on several uncertainties and cover only one balancing technique. The next step in the procedure is to identify the new line's requirements based on preliminary investment cost estimates. Nevertheless, product features may be modified to match current assembly lines, otherwise, data may be submitted to suppliers to provide appropriate solutions. Consequently, there is a high degree of uncertainty in the current product industrialization process, especially as new product variants are to be produced alongside other product variant in the same assembly lines.

3.5 Model validation and testing

The validation and testing of the DMT were based on Caine & Robson's (1993) three step validation process. This process was selected because it was explicitly developed for spreadsheet models, which is the base of the developed DMT. In the process, the first step involves inserting incorrect data into the model in order to test its robustness. This is particularly important if the model is intended for third-party usage (Caine & Robson, 1993). For this thesis, this was accomplished by inserting already known incorrect data. The impacts were then studied, and appropriate changes and features were added to the decision-making tool. For instance, one of the changes related to this step regards the implementation of an IFerror function in order to avoid incorrect data entry. If the result of the task is an error value at any stage during the iterations, the IFerror-function returns the value zero or a blank cell, instead of ending the calculations. Also, the implementation of instructions provides vital information to the user for how to reduce wrong data entry. Furthermore, with the aim of minimizing wrong data entry, colour coding highlighting in which cells the user are supposed to enter values was used.

The second step involves verifying the model, which implies checking the logical relations between the different spreadsheets and ensuring the accuracy of the intermediate and final results (Caine & Robson, 1993). To verify the decision-making tool's accuracy, an already conducted mixed-model assembly line balancing process presented by Groover (2016) was decomposed into comparable steps. The input data from Groover's (2016) calculation was then used in the decision-making tool. Both the intermediate outputs and final outputs of the decision-making tool were then traced through the spreadsheets and compared with the expected results in Groover's (2016) calculations. By following this procedure, with already known correct outcomes, it was possible to easily identify any unexpected and undesired results (Caine & Robson, 1993). This procedure was solely used to test the line balancing part of the decision-making tool. However, this was not applicable to the investment module since it is highly dependent on the received input data, rather than the computation processes within the model.

The third step involves testing the model with data that is similar to the actual data which will be used in the authentic environment where the model will be used (Caine & Robson, 1993).

The testing was accomplished by gathering data from the case company. The decision-making tool was then fed with case company data and the result from the model was compared to old calculations made by the case company. Through this step, it was possible to identify how accurately the decision-making tool can work in an authentic setting (Caine & Robson, 1993). The results gained from this final testing provided satisfactory results according to the case company respondents. However, due to confidentiality, the exact results from the testing will not be shown in this thesis. Instead, hypothetical figures are used to illustrate the decision-making tool's functionality and usability throughout the thesis.

3.6 Trustworthiness

In order to establish trustworthiness, authors and researchers are required to achieve purposeful results, which in turn has the capability of creating fact-based conclusions. In qualitative studies, the traditional heresy of validity and reliability is not a suitable option (Leedy et al., 2019). In its place, Lincoln & Guba (1985) introduced the concept of *trustworthiness*. To establish and achieve *trustworthiness* in a qualitative study, it must, according to Lincoln & Guba (1985) fulfill four criterions: *Credibility*, *Transferability*, *Dependability* and *Confirmability*.

Credibility in information sources is, according to Lincoln & Guba (1985), the most significant trustworthiness criterion. Without credibility in information sources, the findings, discussions and conclusions cannot be identified as credible by the reader (Lincoln & Guba, 1985). By using the technique data triangulation, including interviews, document studies, and focus group, the credibility of information sources in this thesis was established. Credibility might also be increased through peer debriefing (Lincoln & Guba, 1985). This was realized by having researchers and their research exposed and questioned during two oppositions from peer students, but also through having the research carefully reviewed by the assigned supervisor and examinator.

Transferability of a study can be accomplished by writing a thick description (Lincoln & Guba, 1985). The DMT has thoroughly been explained in order to grant readers the possibility of deciding whether it can be applied in their area. Also, by following the steps for developing spreadsheet models as described in the theoretical chapter to develop the DMT, it was possible to ensure the transferability of the research. Following this procedure not only helps the reader to understand how the DMT can be applicable in other settings, but also how similar production development tools can be adapted to fit RMS. The transferability has also been tested by using a case study to test and validate the DMT, in order to establish the functionality in an actual industry setting.

Dependability, in particular the dependability audit, regards providing the reader with the possibility of investigating the research, and with preciseness and openness show how methods have been applied (Lincoln & Guba, 1985). Through carefully describing the research's activities, presented earlier in this chapter, and by following the determined methods the research's dependability was secured. Furthermore, the fifth chapter in this thesis describes how the DMT has been developed, thereby enabling the reader to follow the DMT development procedure.

Confirmability is traditionally regarded as a parallel to the conventional view on objectivity. Usually, confirmability is achieved through a confirmability audit, which contains explaining the process used in the research. This enables the reader to evaluate the consistency between theory, empirical data, and results (Halldórsson & Aastrup, 2003; Lincoln & Guba, 1985). In this research, confirmability was accomplished by each chapter having their standpoint in the research questions, but also through describing the research process in detail, as seen previously in this chapter.

3.7 Ethical and moral perspective

The Swedish Research Council has developed four main criteria which incorporated the most important aspects researchers need to take into consideration when conducting research (Patel & Davidson, 2011). Since the data collection will solely be gathered from a single company, and consist of sensitive data, the handling of data will be significant. In order to establish the confidentiality, collected data will be stored in a safe place only accessible to the authors. The sensitive data will, once the examinator has approved the thesis, be deleted. Furthermore, before conducting the interviews, informed consent will be established. This is, according to Saunders et al. (2016), the highest level of consent. Informed consent regards the respondent giving consent to be a part of the data collection. This consent is based on the respondent having complete information about their participation rights and how the collected data will be used. Furthermore, in the spreadsheet model developed by Weiss (2013), an explicit approval regarding using the model in future research is declared for. This approval validates the use of Weiss' (2013) spreadsheet model in this thesis from an ethical and copyrights perspective.

4 Theoretical findings

The fourth chapter covers the theoretical findings of the thesis. These findings are solely connected to RQ1, RQ2 and RQ4 since these had a direct theoretical connection, whilst RQ3 was developed based on the output of the previous research questions and is presented in the succeeding chapter.

4.1 RQ1 - Which line balancing problem-solving techniques exist in the literature?

The literature study result indicates that several techniques have been used for solving assembly line balancing problems. Early attempts to balance the workload among stations were made through trial-and-error processes. These early models were manually computed by exploring several types of combinations and probabilities. However, this approach was not practical when the problem size increased. Other systematic approaches were later developed in order to face the complexity and scaling of manufacturing systems.

The systematic approaches can be divided into two main categories: *Exact solution* and *Approximate solution.* These differ depending on the approach used to find the workload distribution among stations (Battaïa & Dolgui, 2013). To start, *Exact solution* utilizes the mathematical principle of *integer programming* to calculate the exact solution of the balancing problem by exploring all possible operation combinations. In addition, *integer programming* necessitates more time when working with complex production processes that require buffers and different items. Furthermore, since increasing the number of variables within the assembly line resulted in redundant solutions in certain situations, these methods produced infeasible solutions. Also the logical and physical restrictions (e.g. material handling, manufacturing processes constraints) in the line affects the applicability of Integer programming (Baybars, 1986; Gökċen & Erel, 1998).

Approximate solutions were created to reduce the difficulty of *Exact solutions*. The *dynamic programming* technique is utilized by dividing the balancing problem into subproblems or steps that can be solved independently before being aggregated to find the final solution. The number of potential solutions is decreased at each stage, and only feasible solutions are considered in the later steps. Another approach to use dynamic programming is to minimize the amount of time available for problem solving, which can be done by limiting the running time for the software used to solve the balancing problem (Battaïa & Dolgui, 2013). Both dynamic and integer programming have been widely used in industry and academia to develop software and run simulations for assembly line design.

4.1.1 Heuristic methods

Many researches indicated that integer and dynamic programming has several downsides (Mamun et al., 2012). Using the above-mentioned mathematical and computation methods to solve line balancing problems is too complicated, especially when dealing with practical problems that demand a simple solution. As a result, the *Heuristic methods* were developed with the intention of solving balancing problems in a short time and without complicated calculations (Kharuddin et al., 2019; Mamun et al., 2012).

As per literature review findings, the *Heuristic methods* provide accurate results for practical applications (Bhattacharjee & Sahu, 1987). Nevertheless, different heuristic priority rules have been developed by researchers to be considered while solving ALBPs. Researchers have suggested various types of priority rules which can be used to group tasks in stations (Betts &

Mahmoud, 1989; Scholl & Voss, 1997), and includes, for instance, assigning the operation with the highest or lowest cycle time first. The order of selecting operations can also be based on the number of the following tasks. Similar rules consider other ranking criteria such as the number of following immediate stations and task cycle time divided by the latest station (Scholl & Voss, 1997; Talbot et al., 1986). Based on these rules for every iteration in the grouping stage, an operation with the highest priority is assigned to the available station if the station's cycle time does not exceed the maximum defined cycle time.

Different priority rules result in dissimilar combinations of stations depending on the operations' logical sequence and the variances between tasks cycle time. The priority rules include, for instance, assigning the operation with the highest or lowest cycle time first. The order of selecting operations can also be based on the number of following tasks. However more complicated methods have been developed to fulfill different objectives, for instance *Ranked Positional Weight*, *Kilbridge and Wester Column* and *Largest Candidate Rule* (Sivasankaran & Shahabudeen, 2014; Talbot et al., 1986), the following subchapters highlight these priority rules.

4.1.1.1 Ranked Positional Weight technique

The Ranked Positional Weight technique (RPW) was originally introduced by Helgeson and Birnie (1961). The method's key consideration is that the workload is distributed to stations based on their positional weight. In RPW, the weight is calculated as the sum of task times for all subsequent operations, all the way until the end of the line. The technique includes the following steps:

a) Calculate the weight for all the operations based on the cycle time.
b) Order the operations in descending value, starting with the operation with the highest positional weight.
c) Assign the operations into workstations and give priority to the highest positional weight.
d) Keep the dependence relation between the operations and don't exceed the cycle time of the assembly line (Karabay, 2014; Saurabh Jha & Khan, 2017).

4.1.1.2 Kilbridge and Wester Column technique

The Kilbridge and Wester Column technique was introduced by Kilbridge & Wester (1961). The technique suggests that operations shall be organized based on the order within the precedence diagram and then arranged in columns. Within every column, the operation with the highest cycle time is ranked first, followed by the second-highest cycle time. This procedure continues until all operations are ranked. Thereafter, the operations are assigned to stations based on the given ranking. The steps to apply the Kilbdrige and Wester Column technique are:

a) Order the operations in a precedence diagram and arrange them vertically within columns.
b) Rank the operations within their columns based on cycle time.
c) Calculate the cycle time for every column.
d) Allocate operations in the columns to workstations until the maximum cycle time is reached, and continue assigning the prosses in the next column if possible (Akpinar & Bayhan, 2011; Kilbridge & Wester, 1961).

4.1.1.3 Largest Candidate Rule technique

The Largest Candidate Rule (LCR) technique targets to distribute the load between stations as equally as possible, by ranking operations in descending order starting from the operation with the highest cycle time. Thereafter, the operation is assigned to the stations with consideration to the maximum cycle time of the line. As a result of the steps of this technique, it provides a trade-off between reducing the number of stations and the smoothness of the workload (Bhattacharjee & Sahu, 1987; Olhager, 2013). The technique can be performed through the following steps:

a) Rank all the operations in descending order based on their cycle time, starting from the highest.
b) Assign operations to workstations with respect to the precedence whilst ensuring not exceed the line cycle time.
c) Start at the top of the list and work down by choosing the first feasible operation for allocation to the station.
d) Keep assigning all the available operations to the workstations whilst not exceeding the maximum cycle time (Cortés et al., 2010; Roshani & Nezami, 2017; Saurabh Jha & Khan, 2017).

4.1.2 Summary of line balancing problem-solving techniques

As an attempt to illustrate which line balancing solving techniques exist in the literature, Figure 9 has been created. This figure is a result of the literature study and is summarizing the line balancing techniques classification suggested and used in previous research. Two main systematic approaches to solve ALBPs were recognized: 1*) Exact methods*, which use numerical analysis to investigate all feasible solutions to find the best answer. This approach was discovered to be impractical in the industry due to their difficulty, particularly as the scale of the problem grows. 2) *Approximate methods*, which include both *dynamic programming* and *heuristic methods*. The first employs the same principle as *integer programming*, but with the goal of narrowing the space of solutions. *Heuristics methods*, on the other hand, do not generate optimal solutions for a given situation, but rather use a rational series of steps to find approximate solutions. Furthermore, when assigning assignments to assembly stations, multiple priority rules may be used. The most popular methods and techniques identified in the literature study take operation times, following tasks, positioning weight, or a combination of these, into account.

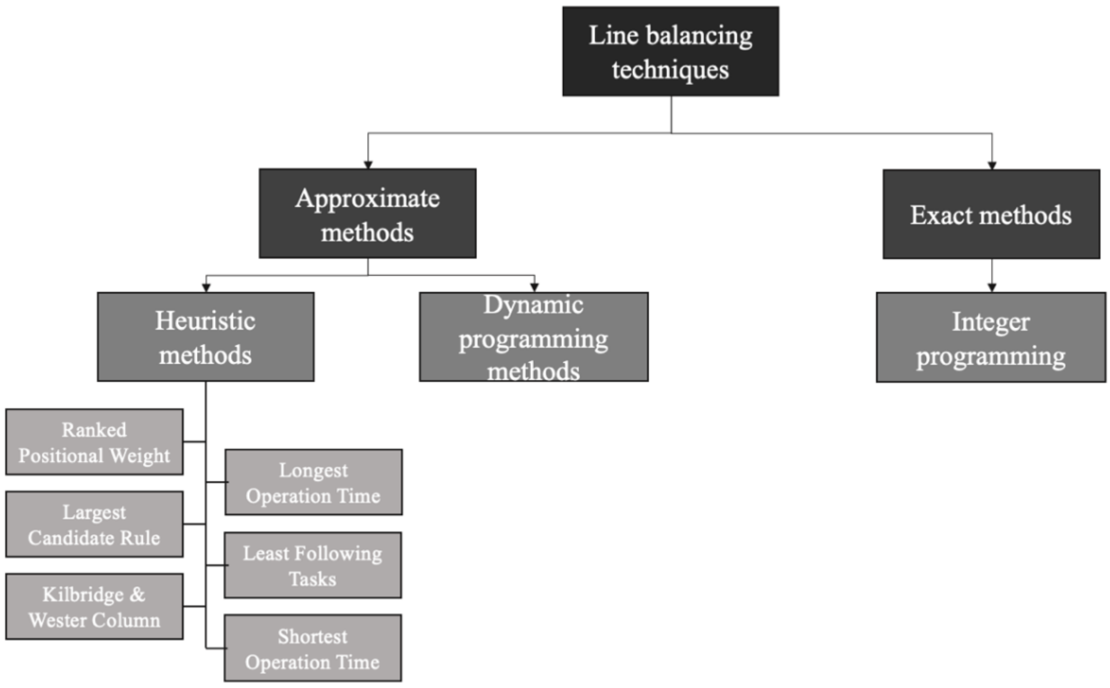

Figure 9 - Line balancing technique classification

4.2 RQ2 – Which investment costs can be considered vital for new assembly lines as a consequence from new product introductions?

The results of the literature study focusing on investment costs indicate that assembly line investment costs are an important factor in a company's long-term economic performance. However, the literature review also shows that among researchers, there is no well-established methodology for estimating assembly line investment costs. The majority of researchers are focusing on developing ways of predicting investments, such as Net present value (NPV) and life-cycle costing (LCC). One of these researches is Tosatti’s (2006), who is presenting a methodology for lifecycle design of production systems. In their research, costs are divided into three categories; investment costs, fixed costs, and variable costs. The investment costs are covering installations and the production system configuration. The fixed costs are, for instance, related overhead and space rent costs. Lastly, variable costs are covering maintenance and energy, i.e. costs dependent on the demand (Tosatti, 2006).

Seldom are researchers focusing on characterising and labelling the actual inputs of these investments. For instance, Bond & Jenkinson (1996) argue that investments are two-folded and comprise of intangible capital, frequently termed human capital, which includes skills and education. The other perspective of investments regard fixed capital (Bond & Jenkinson, 1996). Nevertheless, they do not specify the characteristics further. However, a few papers present detailed assembly line investment costs categorization. Michalos et al. (2012) developed a sophisticated method for developing and evaluating assembly line alternatives, which incorporates the decision needed to be taken when designing an assembly line. In their research, the investment costs are calculated as the total cost for acquiring and installing resources, e.g. machines and tools, needed in the production.

Similarly, Padrón et al. (2009) is presenting a methodology for cost-oriented assembly line balancing problems. Based on their previous research and consulting experience, Padrón et al. (2009) divided investment costs, specifically for highly manual assembly lines, into two main categories; short-term operating costs and capital investment costs. Short-term operating costs cover employee wages and floor space costs. The latter, i.e. floor space costs, include rent and complementary utilities. On the other hand, fixed capital investment costs can be divided into two categories; task-related investment costs and workstation capital investment costs. The former is related to costs required due to the task’s essence. Hence, they are necessary for production to circumvent. These investments include costs related to the purchase of machines, fixtures, equipment, and tools. Contrary, the workstation capital investment costs are associated with standard equipment required at each workstation. These incorporate e.g. chairs, workbenches, and mats (Padrón et al., 2009).

Regarding previous research conducted particularly on investment costs connected to reconfigurable production, the literature study identified the works of Delorme et al. (2016) and Sievers et al. (2017). The former, i.e. Delorme et al. (2016), defined the production line costs in a reconfigurable transfer line as the cost per workstation and cost per CNC machine. Contrary, Sievers et al. (2017) applied a modular production site design, where they considered the fixed capital investment a key component in decision making. This key figure consisted of material cost, plant construction and overhead costs. The former two categories are not specified further, whilst the latter includes engineering and uncertainties costs (Sievers et al., 2017).

4.2.1 Summary of assembly line investment costs

As an attempt to create a uniform classification covering which investment costs can be considered vital in new product introduction, Figure 10 has been created. This figure illustrates the results from the literature study and summarizes the investment costs classification suggested and used in previous research, as described above. The classification of which investment costs has been divided into two major parts; intangible costs and fixed costs. The former is further divided into labour costs, including education and salaries, and floor space costs, including construction, engineering, rent, heating and energy. Fixed costs, on the other hand, is divided into task-related investment costs and workstation investment costs. The task-related investment costs include machines, fixtures, tools and equipment, i.e. costs related to the completion of a task or operation. Workstation investment costs are related to upgrading and enhancing the workstations. These include purchasing chairs, workbenches, and mats.

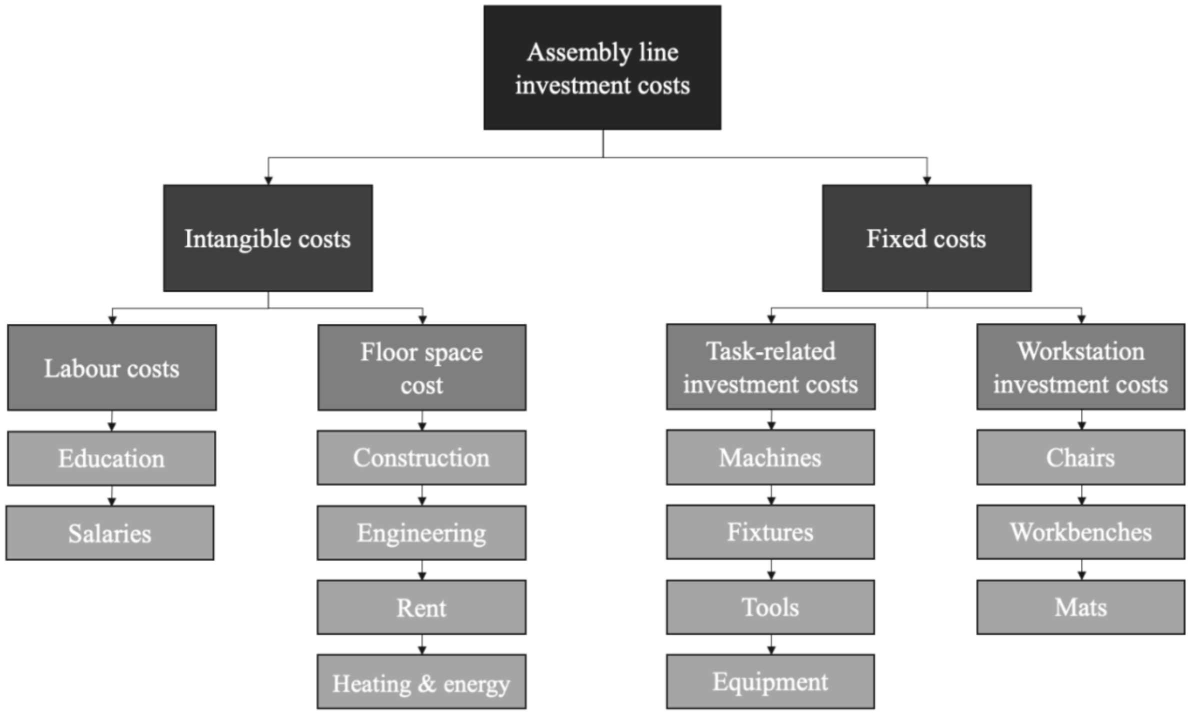

Figure 10 - Assembly line investment costs classification

4.3 RQ 4 – To what extent can criteria in the RMS theory be linked with the attributes of the designed decision-making tool to support its applicability?

The literature study identified a correlation between RMS and mixed-model assembly line balancing as both of these are handling the dilemma of efficiently producing a variety of product variants in the same production system. Because while the earlier model for assembly lines developed by Henry Ford used for mass production for one product. Mixed-model assembly lines aim to produce various products within the same product family (Baybars, 1986; Shtub & Dar-El, 1989). A standard mixed-model line balancing problem intends to define the need to meet a specific performance objective. When addressing a balancing problem, several considerations are taken into consideration based on given data and the objective of balancing. These considerations may include one or more of the following: a given number of products, operations associated with each product, task precedence relations within the line, takt times, product demands, task times, and if the assembly line is equipped with buffers between stations (Becker & Scholl, 2006; Chakravarty & Shtub, 1985; Erel & Gökçen, 1999).

Lohse (2006) linked the responsiveness of assembly lines and the variation of production capacity in highly customized products, such a dynamic environment generates a need for layouts, processes, and workers that support activities in response to production needs. Several researchers have heightened the link between the mixed assembly line and reconfigurability enablers. Koren & Shpitalni (2010) stated three reconfigurability characteristics associated with reconfigurable assembly lines: customization, scalability, and convertibility. Customization relates to the assembly systems ability to assemble all the products in the product family; scalability ensures the system to increase productivity to meet the changing demand and convertibility enables the assembly line to switch between assembling one product to another within the product family in a rapid manner (Koren & Shpitalni, 2010; Youssef & Elmaraghy, 2006). Another key aspect of a reconfigurable assembly system is a modular conveyor system which can be reconfigured to accommodate a variety of components according to the product being assembled (Koren & Shpitalni, 2010).

The model of introducing a new product to the production system for the mixed-model suggested by Fujimoto & Clark (1991) illustrates the new product is scaling up through time. That is associated with increasing the production rate (*Scalability*); hence product introducing models usually start with pilot production and scalability. However, by applying early changes to products and production systems, it is expected to increase the production rate to achieve the market target, a critical RMS aspect (Bellgran & Säfsten, 2009). Ulrich & Eppinger (2016) illustrated the relation between new products and production at pre-production as a challenging stage to fulfil quality and speed requirements. Both two requirements are connected to *Diagnosability* and *Flexibility*, respectively.

Moreover, the production system must identify the root cause of product and process quality issues during ramp-up to rectify them as early as possible to avoid the cost of late changes. The smooth transition between the old and the new product with limited setup time or even without setup time is in line with what Koren (1999) described as assembly line *Convertibility*. To sum up, the literature study results provided insights into the correlation between RMS characteristics and mixed-model assembly line balancing. It also indicated that in order to establish an adequate way of evaluating RMS against mixed-model assembly line balancing, and thus also the decision-making tool, the RMS characteristics need further explanation. The literature study found the previous research by Rösiö et al. (2019) which covers a breakdown of the RMS characteristics into detailed sub-characteristics as an approachable solution to this.

5 Decision-making tool design

The fifth chapter covers the answer to the third research question and is introducing the developed decision-making tool. This is initiated by a description of the DMT concept, assumptions, and delimitations. Thereafter, a detailed description of the DMT follows, covering the structure and computations used. Lastly, the evaluation of the DMT is declared for.

5.1 Decision-making tool outline

The decision-making tool was developed based on the output from RQ1 and RQ2. The general layout and single-model line balancing function were based on the model created by Weiss (2013). This model was expanded to handle MMALBP Type II, whilst also including the heuristic methods described in the previous chapter. The theoretical findings from RQ2 set the foundation for the investment cost terminology, which was complemented and combined with the case study findings. Furthermore, the input data assumptions were carefully considered in close collaboration with the case company. As a result, there is a possibility of including a suitable level of complexity while still guaranteeing industry usability. The decision-making tool is based on the major assumption that two (or more) products are theoretically possible to produce in the same line, without any noteworthy setup times or other constrictions. However, the company might not know if they are compatible from a line balancing perspective due to the cycle times for each task (operation) might vary dependent on the product. Thus, there is a need to use an accurate decision-making tool to help decide whether it is more economically beneficial to produce the products in an already existing line (alternative 1 in Figure 11 below), or to invest in new assembly line(s) and produce the products separately (alternative 2 in Figure 11 below). In modesty, the decision-making tool is simply comparing the idle time and employee costs with the sum of potential assembly line investment costs, and suggest the user to choose the alternative with the lowest final cost.

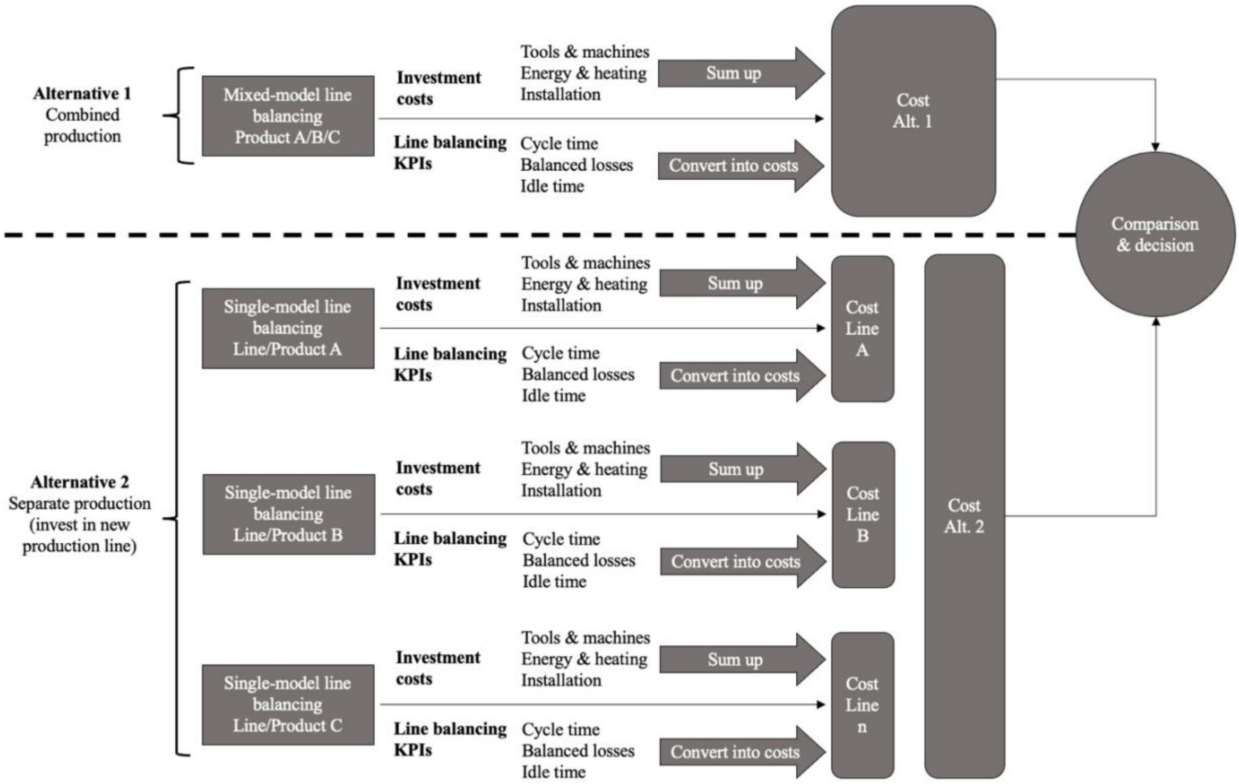

Figure 11 - Decision making tool outline

Since most existing decision-making tools, and in particular existing line balancing tools (e.g. Weiss, 2013), are either too complex to apply in a wider industry setting, or too limited regarding adaption to the focal company, the DMT has been designed with reconfigurability in mind. For instance, the reconfiguration of investment costs, whereas it is possible to either include more cost categories if the user requires a more detailed result, or simply alter the suggested categories to include the case relevant costs. These alternatives provide the user with the possibility of changing the DMT in accordance with their company. Theoretically, the DMT's ability for scalability generates the possibility to test an unlimited number of products, as highlighted in Figure 11 above. However, as informed by the case study respondent, in most situations, companies are solely interested in testing whether a single new product is viable for production in the existing line. This as product development frequently only occurs one at a time. Therefore, the decision-making tool is solely structured to handle three products, whereas two are new products. In the case where several products are already produced in the existing line, and the goal is to determine whether it is possible to produce another product in the same line, the authors suggest to pre-calculate the combined task times for the products produced in the separate line.

Once the user has inserted the necessary inputs, the DMT automatically conducts both mixed-model assembly line balancing and single-model assembly line balancing for all products. The latter is achieved by using four different priority rules. The user then can select either select the most line-efficient option as suggested by the DMT, or another priority rule if recognized as being a better fit for the company. The mixed-model line balancing is using the priority rule *Longest Operation Time*, however, the cycle time can be calculated in different ways. This decision-making tool is conducting line balancing based on two ways: *Max task time* and *Weighted average task time*. Based on, for instance, the company's product variety, the user has the possibility to choose which task time fits their unique production setup.

Apart from the aforementioned assumptions, the decision-making tool is designed based on the following assumptions:

- Task times are calculated beforehand by the user.
- No setup time is required when producing several product variants in the same line.
- Task times are including times for walking, moving products, and preparing the next task.
- All parameters in the DMT are assumed to be deterministic.
- Task times are fixed, unless changed by the user.
- There is not a fixed set of stations, this is calculated by the decision-making tool.
- The total time of a task cannot exceed the required takt time. If a task is exceeding the required takt time, the user must divide the task into two or more tasks in order for the tool perform the line balancing.
- The assembly lines tested in the decision-making tool is constructed as serial lines, not as U-shaped lines.
- The input parameters are correct, for instance, the predecessors must follow a logic and true diagram.
- Each station needs exactly one worker.
- Fixed costs are based on the entire investment costs on, i.e. no depreciations are calculated in the DMT. If depreciation should be included, the user must take this into consideration when inserting input values.
- No production order sequencing is taken into consideration in the DMT. Instead, products are calculated based on the overall production capacity on a yearly basis.

- The product quality does not change when producing the new product(s) in either separate or combines assembly lines.
- In the Monte Carlo simulation, the DMT operates on the basis that the outputs are normally distributed.

5.2 Decision-making tool structure & process steps

A modular structure was used to create a simple and functional tool that incorporates all of the previous chapter's assumptions and produces the desired results. The modular structure combines investment costs, Monte Carlo simulation, and a line balancing into a unified platform. The decision-making tool consists of 21 Microsoft Excel spreadsheets, which are connected through a variety of mathematical and logical formulas. The tool is further broken down into 13 major steps. Figure 12 illustrates the flow of information throughout the DMT. The input data is inserted by the user and includes product data, general data and investment costs. The combination of products, the line balancing module, and the Monte Carlo simulation for investment costs are conducted automatically by the tool. Therefore, these have been represented by three black boxes. Similarly, the output from the three black boxes is summarized automatically, and has also been illustrated through a black box. Based on this summary, the tool provides the user with the suggested decision which the user then is supposed to validate and analyse.

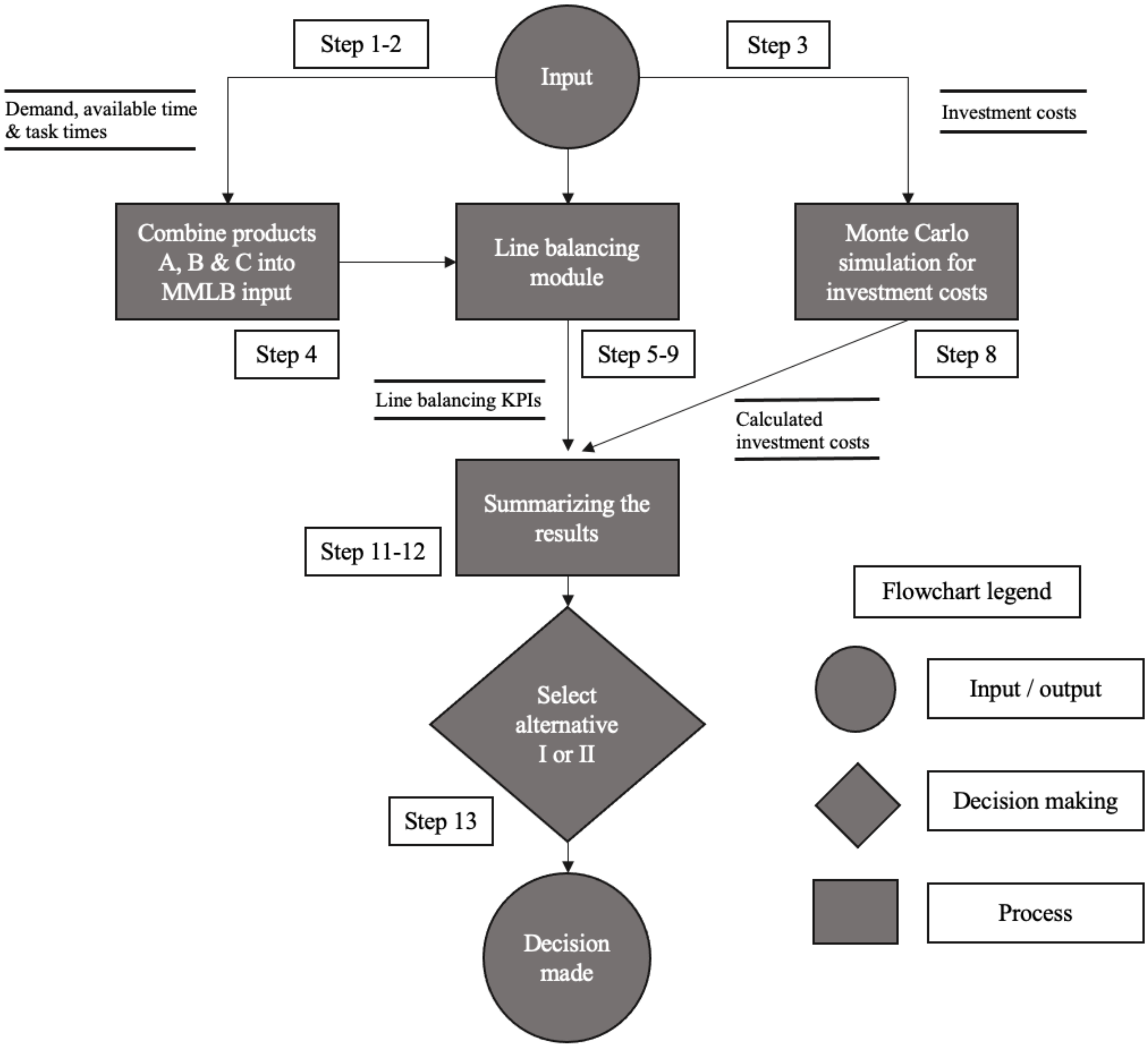

Figure 12 - Information flow and step connection

The first spreadsheet in the DMT is an introduction sheet. In this, the step and task linkage, general decision-making tool logic, input assumptions and update logic are explained. The step and task linkage introduce the tool's outlines to the user by connecting the DMT steps to whether the user's action is required, or if it regards a step automatically computed by the tool.

Each step is also connected to a brief description of the task required and where the action should occur, as a means to further clarify the procedure (see Figure 13 below).

Steps	Responsible	Sheet	Task
Step 1	User	LB Input data	Insert product data
Step 2	User	LB Input data	Insert general data
Step 3	User	Investment Input Data	Insert investment data
Step 4	Program	Combine ABC	Calculate task times for combined production
Step 5	Program	LB WATT ABC	Conduct mixed-model line balancing using Weighted Average Task Time
Step 6	Program	LB MAX ABC	Conduct mixed-model line balancing using Max Task Time
Step 7	Program	LB Line A	Conduct single-model line balancing for product A using four different priority rules
Step 8	Program	LB Line B	Conduct single-model line balancing for product B using four different priority rules
Step 9	Program	LB Line C	Conduct single-model line balancing for product C using four different priority rules (if feasible)
Step 10	Program	MC	Perform Monte Carlo simulation for investment costs
Step 11	Program	Detailed results	Compare costs for both alternatives and all priority rules
Step 12	Program	Result	Present comparison between best alternative and technique
Step 13	User	Result	Analyse output

Figure 13 - Decision-making tool steps and task linkage

In step 1, the user is to insert certain product values, such as task names, task times and the predecessors of each task (Figure 14). The default setup for the tool is to receive inputs for three products sharing the same tasks. However, if one of the tasks is not applicable for the product, the user shall input 0 seconds for the task (as seen in the example below). Also, if the user is dealing with two product variants, rather than three, the user should only enter input data for the relevant products (A & B), while entering 0 in task times for product C. Once the user enters the task's name, the tool automatically provides a unique code for the task name through an alphabetic coding system. These coded names will be used internally in the rest of the tool for practical reasons.

Product A				
Task name	Task code	Task time (s)	Predecessor task	Number of following tasks
ST040	A	185	--	7
ST041	B	245	A	6
ST042	C	126	B	5
ST043	D	333	C,A	4
ST044	E	188	D	3
ST045	F	249	E	2
ST046	G	100	F	1
ST047	H	300	G	0

Product B				
Task name	Task code	Task time (s)	Predecessor task	Number of following tasks
ST040	A	180	--	7
ST041	B	243	A	6
ST042	C	181	B	5
ST043	D	301	C	4
ST044	E	100	D	3
ST045	F	120	E	2
ST046	G	242	F	1
ST047	H	241	G	0

Product C				
Task name	Task code	Task time (s)	Predecessor task	Number of following tasks
ST040	A	0	--	7
ST041	B	0	A	6
ST042	C	0	B	5
ST043	D	0	C	4
ST044	E	0	D	3
ST045	F	0	E	2
ST046	G	0	F	1
ST047	H	0	G	0

Figure 14 - Task input data

Step 2 regards the user's input of general information. This in terms of available time, overall equipment efficiency target (OEE), and the demand for every product variant (see Figure 15 below). Based on the inserted data, the decision-making tool calculates the total demand per year by adding the yearly demand for each product together. The actual available production time is thereafter calculated by multiplying the total production time with the overall equipment efficiency target (Equation 1).

$$Actual\ available\ production\ time\ \left(\frac{hrs}{year}\right) = Total\ production\ time\ \left(\frac{hrs}{year}\right) * OEE\ target \qquad (1)$$

Thereafter, the demand per hour is calculated by dividing the total demand per year by actual production hours per year. Lastly, the required task time for the assembly line is calculated, as seen in Equation 2.

$$Required\ cycle\ time\ (s) = \frac{Actual\ available\ production\ time\left(\frac{hrs}{year}\right) * OEE\ target * 3600}{Total\ demand\ per\ year} \quad (2)$$

	Yearly volume Product A	Yearly volume Product B	Yearly volume Product C
Demand per year	2000	3200	1500
Weighted demand	0,3	0,5	0,2
Required cycle time	5508	3443	7344

Total production time per operator (hrs/year)	1800
OEE target	85%
# of shifts	2
Total demand per year	6700
Actual available production time (hrs/year)	3060
Demand per hour	2
Required cycle time for combined line (s)	1644

Figure 15 - General information input

Step 3 involves inputting the data for the two alternatives, i.e. either investing in a new assembly line or upgrading the existing line to produce the new product within the same line. These investment costs are divided into fixed investment costs and intangible costs. The former is covering investment costs for machines, equipment, tools, installation, renovation, spare parts etc. Operating costs on the other hand, is covering the estimated annual costs for running the assembly line. The indirect costs have been divided into two main categories: labour costs and floor space costs. The further detailing of these categories is illustrated in Figure 16 below. Both the estimated cost, and standard deviation of each cost post should be inserted. If the user reckons the standard deviation not necessary, this part can be skipped. Once the necessary data has been inserted, the tool calculates the total capital investment cost according to Equation 3.

$$Total\ investment\ costs\ = \sum Fixed\ costs + \sum Intangible\ costs \quad (3)$$

Investment in new line

Fixed costs	**Expected**	**St.dev**
Task-related investment costs		
Machines	200 000 kr	10%
Fixtures	100 000 kr	10%
Tools	100 000 kr	10%
Equipment	100 000 kr	10%
Spare parts	100 000 kr	9%
Other		
Workstation investment costs		
Chairs	200 000 kr	10%
Mats	100 000 kr	10%
Workbenches	100 000 kr	10%
Other		
Intangible costs		
Labour costs		
Education	50 000 kr	10%
Salaries	50 000 kr	10%
Other	50 000 kr	10%
Floor space costs		
Construction	20 000 kr	10%
Engineering	2 000 kr	10%
Rent	2 000 kr	10%
Hearing & energy	2 000 kr	10%
Other	2 000 kr	10%
Grand total	1 178 000 kr	9,94%

Upgrade of existing line

Fixed costs	**Expected**	**St.dev**
Task-related investment costs		
Machines	200 000 kr	10%
Fixtures	100 000 kr	10%
Tools	100 000 kr	10%
Equipment	100 000 kr	10%
Spare parts	100 000 kr	9%
Other		
Workstation investment costs		
Chairs	200 000 kr	10%
Mats	100 000 kr	10%
Workbenches	100 000 kr	10%
Other		
Intangible costs		
Labour costs		
Education	50 000 kr	10%
Salaries	50 000 kr	10%
Other	50 000 kr	10%
Floor space costs		
Construction	20 000 kr	10%
Engineering	2 000 kr	10%
Rent	2 000 kr	10%
Hearing & energy	2 000 kr	10%
Other	2 000 kr	10%
Grand total	1 178 000 kr	9,94%

Figure 16 - Investment input data

In step 4 the program combines the input data for the product variants to create a mixed-model line based on two scenarios: a pessimistic scenario and an optimistic scenario (Figure 17). The former, i.e. *Max Task Time*, is taking all potential products into consideration and sets the time for a combined task based on the highest possible time for that particular task. The optimistic scenario, i.e. *Weighted Average Task Time*, is calculating the task time for a combined task by assuming the products' demands are uniformly distributed based on the weight of the product of the total demand. The outputs gained from the two scenarios are two combined lines for all products with a set of activities, and new task times are calculated based on the weighted demand. The task times calculated in this sheet is used as the new input for the sheets in step 5 and 6. In these steps, the tool is following the line balancing procedure described by Weiss (2013) and uses the priority rule *Longest operation time* to select tasks.

Combined Product ABC			
Task code	Weighted average task time	Max task time	Precedessor task
A	33	185	--
B	45	245	A
C	29	181	B
D	58	333	A, C
E	25	188	D
F	31	249	E
G	34	242	F
H	48	300	G
		0	
		0	

MMLB Combined				
Task name	Task code	Task time (s) A	Task time (s) B	Task time (s) C
ST040	A	185	180	0
ST041	B	245	243	0
ST042	C	126	181	0
ST043	D	333	301	0
ST044	E	188	100	0
ST045	F	249	120	0
ST046	G	100	242	0
ST047	H	300	241	0

Figure 17 - Calculation of weighted task time and max task time

In step 7, 8 and 9 the tool automatically applies and calculates the single-model line balancing procedure as described by Weiss (2013). This is calculated separately for the different products by considering yearly demands for every unique product. The main difference between these steps and step 5 and 6, is since they are conducting single-model assembly line balancing, the possibility of applying a variation of priority rules exists. Four different priority rules have been used in the decision-making tool: *Longest operation time*, *Most following tasks*, *Shortest operation time* and *Least following tasks*. These were chosen due to their applicability in the Microsoft Excel model (Weiss, 2013). The outputs from the spreadsheet in steps 7, 8 and 9, are identical to step 5 and 6, and covers for instance the idle time and line efficiency, but with the exception of showing the outputs for all priority rules simultaneously.

In step 10, as a means to minimize uncertainty in estimating future investment costs, the Monte Carlo simulation method is used, see Figure 18 below. The tool is performing a Monte Carlo simulation by running 500 trials of the estimated investment costs and possible standard deviation for each alternative. Thereby 500 results are automatically computed without requiring any effort from the user. Once this has been accomplished, the tool calculates the mean value for all these results, providing the user with a realistic final output.

Investment in new line				
Fixed costs	Expected	St.dev	Stdev	First simulation
Task-related investment costs				
Machines	200 000 kr	10%	20 000 kr	180 833 kr
Fixtures	100 000 kr	10%	10 000 kr	97 273 kr
Tools	100 000 kr	10%	10 000 kr	85 333 kr
Equipment	100 000 kr	10%	10 000 kr	102 549 kr
Other	100 000 kr	9%	9 000 kr	116 032 kr
Workstation investment costs				
Chairs	200 000 kr	10%	20 000 kr	193 088 kr
Workbenches	100 000 kr	10%	10 000 kr	113 851 kr
Mats	100 000 kr	10%	10 000 kr	107 910 kr
Other	0 kr	0%	0 kr	0 kr
Intangible costs				
Labour costs				
Eduation	50 000 kr	10%	5 000 kr	45 752 kr
Salaries	50 000 kr	10%	5 000 kr	61 311 kr
Other	50 000 kr	10%	5 000 kr	48 065 kr
Floor space costs				
Construction	20 000 kr	10%	2 000 kr	20 288 kr
Engineering	2 000 kr	10%	200 kr	1 651 kr
Rent	2 000 kr	10%	200 kr	2 095 kr
Heating & energy	2 000 kr	10%	200 kr	2 060 kr
Other	2 000 kr	10%	200 kr	1 948 kr
Grand total costs	**1 178 000 kr**	**9,4%**	**116 800 kr**	**1 180 038 kr**

Min	1 089 263 kr
Max	1 269 361 kr
St.dev	37 494 kr
Mean cost	**1 175 846 kr**

Upgrade of existing line				
Fixed costs	Expected	St.dev	Stdev	First simulation
Task-related investment costs				
Machines	200 000 kr	10%	20 000 kr	202 200 kr
Fixtures	100 000 kr	10%	10 000 kr	108 409 kr
Tools	100 000 kr	10%	10 000 kr	91 150 kr
Equipment	100 000 kr	10%	10 000 kr	104 769 kr
Other	100 000 kr	9%	9 000 kr	102 683 kr
Workstation investment costs				
Chairs	200 000 kr	0%	0 kr	200 000 kr
Workbenches	100 000 kr	10%	10 000 kr	97 362 kr
Mats	100 000 kr	10%	10 000 kr	97 303 kr
Other	0 kr	0%	0 kr	0 kr
Intangible costs				
Labour costs				
Eduation	50 000 kr	10%	5 000 kr	57 681 kr
Salaries	50 000 kr	10%	5 000 kr	43 507 kr
Other	50 000 kr	10%	5 000 kr	40 249 kr
Floor space costs				
Construction	20 000 kr	10%	2 000 kr	16 648 kr
Engineering	2 000 kr	10%	200 kr	1 982 kr
Rent	2 000 kr	10%	200 kr	2 124 kr
Heating & energy	2 000 kr	10%	200 kr	2 182 kr
Other	2 000 kr	10%	200 kr	1 789 kr
Grand total costs	**1 178 000 kr**	**8,8%**	**96 800 kr**	**1 170 038 kr**

Min	1 089 263 kr
Max	1 269 361 kr
St.dev	37 494 kr
Mean cost	**1 175 846 kr**

Figure 18 - Monte Carlo simulation

In step 11 the decision-making tool is summarizing the detailed result for all previous calculations, including the line balancing parameters for the two alternatives. Also, the spreadsheet illustrates the task allocation for each station through colour coding. Furthermore, the comparison between the two alternatives is highlighted through figures and colour coding. This spreadsheet is intended mainly for users who desire a deeper insight into the outputs of the tool. In step 12, the decision-making tool uses the exact data for visualizing and summarizing the outputs for the two alternatives. The tool is converting the line balancing KPIs into costs and is thus able to compare these with the investment costs. These are then compared, and a final decision based on the lowest cost is suggested (Figure 19). In the final step, i.e. step 13, the user shall analyze the result in order to completely understand the impact of the decision on the company.

	Alt 1 Separate	Alt 2 Combined
Line balancing KPIs		
# of stations	6	5
Idle time per cycle (hrs)	0,37	0,19
Line efficiency (average)	63%	81%
Balance losses (average)	37%	19%
Production costs		
Balance loss cost (per year)	2 192 008 kr	946 434 kr
Sum	**2 192 008 kr**	**946 434 kr**
Fixed investments costs		
Investment costs	650 648 kr	62 000 kr
Intangible costs		
Area costs	155 963 kr	29 114 kr
Energy consumption	20 616 kr	20 217 kr
Employees	572 027 kr	840 969 kr
Sum	**1 342 610 kr**	**1 013 111 kr**
Grand total:	▽ **3 534 530 kr**	△ **1 959 681 kr**

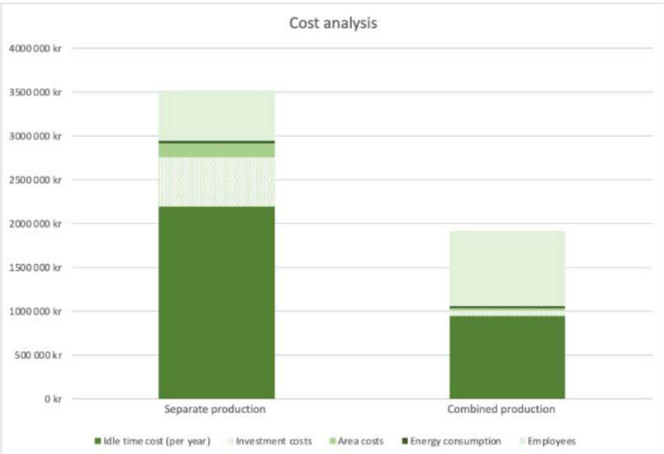

Figure 19 - Final result display

5.3 Evaluation of the decision-making tool

During the focus group occasion, the feedback gained underlined the case company's necessity of using the DMT for two primary reasons. Firstly, the participants indicated that the level of uncertainty is frequently high during the early phases of new product development, hence the need to make fact-based decisions is evident. Secondly, in line with the case company's vision of transitioning towards RMS, the decisions regarding how and where to produce a new product will increase in frequency. Therefore, a structured and fact-based procedure needs to be established in order to support this transition. The participants pointed out that the developed DMT will indeed help in facilitating these decisions, and thus also take one step in the process of moving towards RMS. Furthermore, the output of the DMT was recognized as being a sufficient decision to continue the next step in the product development process. Because, the decision regarding whether the new product(s) should be produced in an already existing assembly line, or to invest in a new assembly line has been taken, will be forwarded to production engineers. These employees will then consider it when designing and purchasing the necessary equipment for the new setup.

The participants also found the DMT to be similar to the tools they are using in, for instance, production planning and financial estimations. Establishing a similarity and coherence between new and old tools was identified as an important factor since it reduces the time required for users to understand the tool. However, it was declared that some parts in the DMT required rephrasing in order to match the terminology used in other tools. On this topic, the participants also approved the choice to create the DMT in Microsoft Excel. The approval was based on the argument that the case company has other Microsoft Excel tools for scheduling and financing functions which make new users instantly familiar with the DMT and reduces the effort required for training new users. Likewise, due to the existing integrability between the DMT and the case company's other tools, the participants pointed towards the future possibility of directly connecting several tools in order to further streamline the product development process.

Moreover, the input data required for the DMT to conduct the line balancing module was recognized as easily being gathered from the production software AVIX, which the case company frequently uses. The participants also provided insights into how historical data used to estimate the time required to do every move in the assembly activities can be used an input for the DMT. Likewise, the participants found the level of complexity in investment costs to be at a satisfactory level. Because, using NPV and LCC was recognized as being far too detailed and complicated to implement during the stage when using the DMT. The investment costs were found to easily being gathered through rough estimation, which is already performed in the case company's current procedure. The Monte Carlo simulation was received with praise as it facilitates the reduction of investment costs estimation uncertainty, whilst not requiring any significant effort from the user.

During the focus group, it was also confirmed that there are two levels of users who will operate the tool: users on a technical level and on a managerial level. The former regards user who can edit the tool and have a deep understanding of intermediate steps. The latter includes users who are solely interested in the final result, and are therefore not interested in how the DMT has reached the decision. Due to the existence of these user levels, the participants in the focus group found it necessary to provide enough information on each Microsoft Excel sheet so users on the technical level will easily understand the process and logic in the DMT. Regarding this, it was also recommended that users could have different levels of access to the tool since some worksheets will be hidden. This restriction reflects the tool's flexibility to answer questions on both managerial and technical levels.

6 Analysis & discussion

The sixth chapter beings with an analysis and discussions of the research questions. Thereafter the methods used in the thesis are discussed.

6.1 Analysis and discussion of findings

The discussion of findings has been divided into four parts, each covering the analysis and discussion for a unique research question.

RQ 1 - Which line balancing problem-solving techniques exist in the literature?

The first research question was addressed by a literature review, and the basic assumptions of assembly line balancing problems were established and categorized. A selection of the identified line balancing problem-solving techniques was used to develop the decision-making tool. These were selected based on usability and possible integration with Microsoft Excel functions. Product diversity drives assembly line balancing problems categorization into two types: single model assembly lines and mixed-model assembly lines. Conversely, ALBP is classified based on the goals of line balancing; Type I problems consider an assembly line with a set number of stations, with the goal of increasing production rate, while Type II problems presume constant process times with the goal of increasing production capability by reducing delay time (Erel & Sarin, 1998; Watanabe et al., 1995).

The result of the literature study also exposed an incoherent view on solving line balancing problems. Many techniques have been developed throughout the years, which all vary in complexity and usability. This might explain why the field of line balancing techniques is very broad, and why new techniques are continuously being developed. Though, there is no approach that fits for all types of problems, and newly developed techniques often seem to solely provide solutions to a specific problem. This issue might partly derive from the unique situation companies are in when entailing to conduct line balancing, and thus creating a generic technique is incredibly difficult. This might be a reason why very simple heuristic solutions, such as RPW and LCR, have lasted amongst theoreticians and are among the most commonly used techniques in the industry.

Many approaches have been established to address both types of problems. To begin, integer programming seeks exact solutions to problems by exploring all possible solutions, while dynamic programming divides problems into sub-steps and excludes the space of investable solutions. Both techniques were found to be complicated to apply in the industry, the algorithms of solutions become quite complex when the number of stations increases. Heuristic approaches were introduced to fulfill the limitations of these techniques. The heuristic approaches generate approximate solutions based on common sense and logical sequence of applying the line balancing assumptions and priority mechanisms. The three above-mentioned techniques have the same goal in mind: minimizing balance delay and create a more uniform workload distribution among stations in the line. Different dedicated software’s developed based on these algorithms.

The literature review generated only four articles when searching with the combination of "Reconfigurable manufacturing system" OR "RMS" AND "Mixed-model assembly line". This limited number of articles indicates that the concept of reconfigurability is still ambiguous and not as common in operations research academia. Additional case studies can reveal how effective are those approaches in different industrial setups.

The answer to RQ1 is summarized in Figure 9; line balancing strategies will differ depending on the goal of the balancing, product variation within the line, or the level of accuracy needed. Where an approximate solution with a high degree of applicability is required, heuristic solutions are the most flexible. Moreover, as far as we know, no general solution has been created to match the framework of RMS. The limited number of publications regarding mixed-model assembly line balancing within RMS context makes it difficult to understand the implications of different balancing techniques on the performance of RMS characteristics. It is also important to remember that the limitation of both *Exact* and *Approximate* methods are related to the accuracy and time efficiency of the calculations mainly. That means a future production system with a low level of uncertainty and timely data exchange within the entire industrial supply chain may not have to face the trade-offs between time-consuming calculations and accurate line balancing results. Such a future production system may benefit from the location in the spectrum of new industry 4.0 trends.

RQ 2 – Which investment costs can be considered vital for new assembly lines as a consequence from new product introductions?

In order to answer the thesis's second research question, the results gathered from the case study and literature study on assembly line investment costs were used. This resulted in Figure 20 below, which indicates the investment costs to be considered vital for a new assembly line as a consequence from new product introductions. This categorization set the foundation for the investment cost module in the decision-making tool.

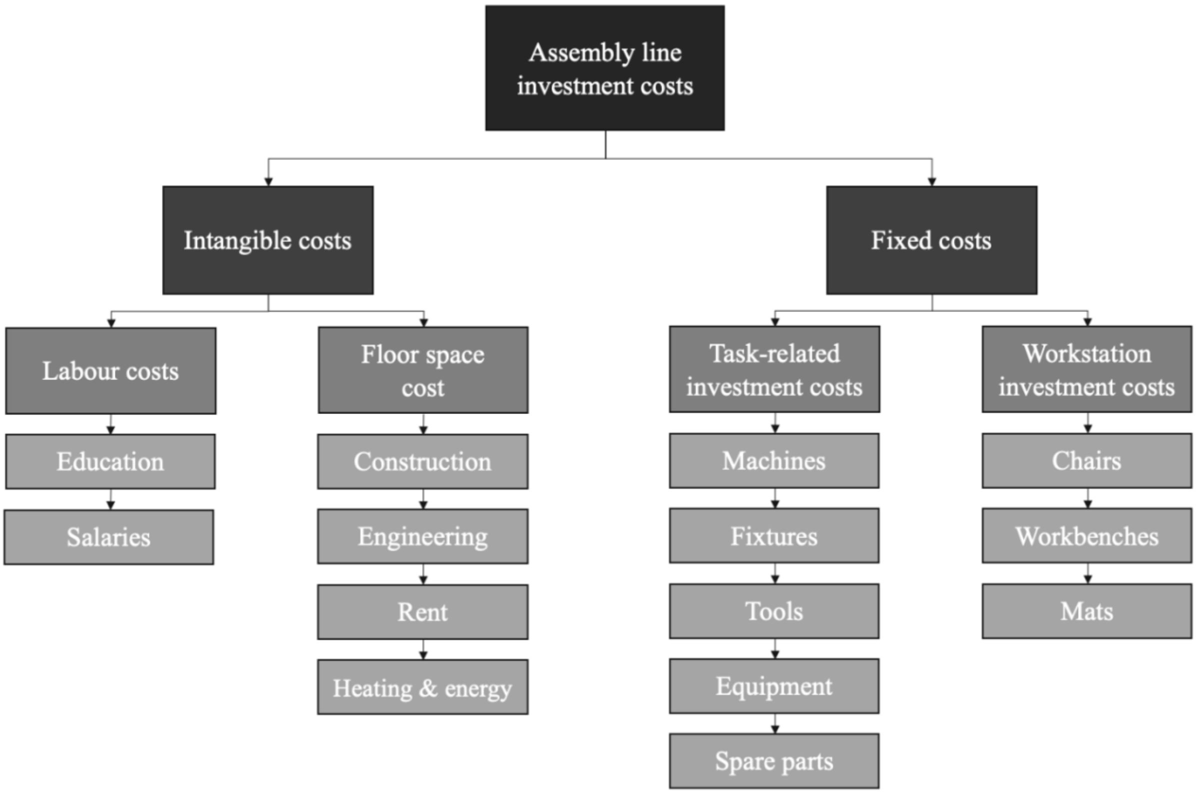

Figure 20 - Combined assembly line investment cost categorization

The literature study's result exposed that the majority of previous research within investment costs has not focused on the detailing of production investment costs, but rather categorizing those into overarching factors. Researchers who actually did specify costs, e.g. Padrón (2009) primarily base their inputs on their experience gained from consulting work. This is an indication of that most research is not focusing on detailing the investment costs, perhaps due to those normally being unique to companies. Also, since larger companies tend to already have customized and developed ways of calculating their own investments in detail, as highlighted in the case study, researchers might have neglected using a specific terminology as it does not interfere with the overarching model functionality. The case study results strengthen this argument and indicate a similar conclusion. The case company is namely using a similar investment cost structure and terminology as depicted in Figure 20. However, these structures are not completely identical, and the case company are foremost including in the investment costs clearly related to the case company.

As for the RMS specific investment costs, the literature study results indicate that these are not significantly differing from costs related to DMS and FMS. Furthermore, since a production system is seldom fully reconfigurable an optimal solution for a production system consists of a combination of the three production systems simultaneously. Hence, even though a production system has been classified as RMS, it might still consist of partly being characterised as FMS and DMS. This is correlating with the results gained from the case study. Because, the case company has thus far not developed specific economic investment calculus nor made any adjustment to the current structure in order to fit specifically for RMS. This lack of adjustment might perhaps derive from the fact that the case company still having an overarching part of their entire production facility as being characterised as FMS and DMS, not RMS. Or perhaps due to the relative newness of RMS, and hence no established way of including the RMS specific characteristics have yet been developed. Studying the sub-characteristics of RMS, as described by Rösiö et al. (2019), it is also possible to relate the absence of RMS integration to the investment cost terminology simply due to a lack of necessity. Because, the investment costs covering for instance machines, tools and fixtures, which are a major part in the work of Rösiö et al. (2019), are already included in the investment cost terminology, for instance in the research by Padrón et al. (2009), Delorme et al. (2016) and Michalos et al. (2012). The aforementioned investment costs are solely describing the costs on a principal level, not the implications of those. Thereby the investment cost terminology might not require major updates in order to realistically reflect RMS, at least not during the early stages of new product development.

Even in research where NPV and LCC calculations are present, as in the works of Tosatti (2006), the costs are simply examples of what to include under certain suggested investment cost headings and not specified any further. Using an investment calculation such as NPV or LCC would indeed increase the accuracy of the investment output. However, as NPV and LCC are very detailed and complex investment calculations, primarily used when making specific investment decisions, these can be reckoned as not suitable to use during the early stages of new product development. Instead, following the procedure in the case company seems like a more suitable option. Since, as shown in the case study results, the case company only performed a rough investment cost estimation during the early stages of new product development, whilst NPV was performed once making the actual investment decision.

To conclude, the results from the literature review and document study provided a new categorization of which investment costs can be considered vital for a new assembly lines as a consequence from new product introductions. However, even though these investment costs are covering both a theoretical and empirical aspect, the usability can be recognized as being limited. This since investment cost terminology is a particularly subjective area, where companies tend to have their own specific way of structuring investment costs, as proven by the vast irregularities which the literature study exposed. The suggested structure in this thesis was found to be sufficient for the case company to utilize the decision-making tool, whilst also being general enough to cover the possibility of other companies also using the decision-making tool without recognizing the need to alter the investment cost terminology. On this topic, the theoretical findings and document study findings exposed almost identical investment costs, hence the figure previously illustrated in Figure 20 does not differ significantly from Figure 10 covering the theoretical findings. The focus of this report implied that the overarching discussion should not regard which wording to use when describing the investment costs, but rather ensure to cover all relevant costs for a new assembly line through collecting data from both literature and document study. Similarly, since the output form RQ2 was used as an input for developing the decision-making tool, solely covering all necessary investment costs should suffice for providing an accurate result to the research question.

RQ 3 – Can a decision-making tool be designed to evaluate new product introductions which considers both line balancing KPIs and investment costs in an assembly line?

In order to answer RQ3, the findings from RQ1 and RQ2 were used. These findings set the foundation for the decision-making tool's two black-box modules. The first module was covering conducting single-model and mixed-model line balancing, while the second module was related to investment costs. A tailored model was created based on the design guidelines for spreadsheets developed by Caine and Robson (1993). Data was gathered through a single-case study, including interviews with the supervisor from the case company, document studies and a focus group. The latter aided in assessing market practices against the various theoretical approaches. By using the aforementioned procedure, the new decision-making tool was constructed based on Weiss' (2013) model. Following that, in multiple iterations, mixed-model assembly line balancing, investment costs, and Monte Carlo simulation were added to the decision-making tool. This technique allowed for design agility and assisted in the correction and tracing of errors within the spreadsheets. Finally, for validation and testing purposes, the line balancing module solved examples from Groover (2016) and the results were compared with the correct answers given by Groover (2016).

A review of the literature revealed multiple line balancing techniques. However, the model developed by Weiss (2013) was found to be the most adequate to the constraints considered in this research. Primarily since it deems priority rules and adopted a modular structure. By creating the models based on an already existing model, the authors were able to focus on the main purpose of this thesis, i.e. to create a decision-making tool specifically for RMS. Nonetheless, the previous model had several drawbacks that needed to be addressed if it wanted to adapt it to mixed-model assembly line balancing and RMS and ensure user-friendliness. Because, the old model seemed to be working to solve a specific solution, but not generalizable and usable in a wider industrial setting continuously. One of the identified drawbacks regards for example modifying the model, which is a relatively difficult task in Weiss' (2013) model. Another downside of the former model is the naming of operations. If one of the names is part of another activity name, the algorithm will generate an error because the task name is verified using the offset function. Using a more sophisticated technique to conduct MMALB, for instance through *Integer programming* would perhaps provide a slightly more accurate result, but would simultaneously increase the tool's complexity significantly. Hence solely changing the combined task time using *Max Task Time* and *Weighted Average Task Time*, and thereafter use the priority rule *Longest operation time* to select task order, facilitated an increased tool usability.

Even though the model presented by Weiss (2013) was a valid starting point for developing the new decision-making tool, the previous model was recognized as not being user-friendly when it comes to adding new tasks. Because, tasks were needed to be added in between existing tasks, and following edits at other sheets were required. In contrast, while in the DMT developed in this thesis was developed in a way that the user easily can add more tasks, without affecting the rest of the model. The maximum possible number of tasks in each assembly line in the DMT is set to 50, with the option of using any number of operations less than the maximum. The previous model put redundant effort on the users, for instance, task names were needed to be changed into alphabetic manually. This makes the model sensitive letters case and may be a source of model failures, which can make the tracing of tasks more difficult. In order to tackle this issue, auto coding functions were added to the DMT. The auto coding was created to allow the user to add the real names of the tasks and the tool would create internal alphabetic coding for every task. This internal coding was then used throughout the computations. Another function added to the DMT was colour coding for stations. In the line balancing result spreadsheet, every task assigned within the same stations has been highlighted with the same colour. By adding this function, the user is able to easily identify which tasks have been assigned to each station.

The development of the investment module faced not only minor implications of combining theoretical findings and empirical data to create and find a solution which is both general, but also fitting the relevant stage in the product development. The DMT was created to establish a way to structure early investment calculations by using a combination of both theoretical investment costs and the one identified in the document analysis and through interviews. Several investment costs, without taking the depreciations into consideration, were used in the DMT as direct inputs to minimize the model's complexity. However, the investment calculation black box is designed to be flexible enough to enable the user to easily change the investment costs terminology without disrupting any corresponding steps. Furthermore, in order to decrease the uncertainty of estimating investment costs, the Monte Carlo simulation was added to the DMT. By doing this, it was possible to reduce some of the uncertainty connected to estimating investment costs at an early product development phase. However, this input has been developed in a structure where the users themselves have the option to choose to implement this procedure. Because if not, the user simply has to insert a value of 0 for the standard deviation with the aim of neglect this during the simulation. The output will then only consist of the summarized expected outcome for the investment cost posts. Hence, providing the user with the option of adapting the usage of Monte Carlo simulation according to their preferences might also enhance a broader usability.

RQ4 – To what extent can criteria in the RMS theory be linked with the attributes of the designed decision-making tool to support its applicability?

As a means to investigate whether the created DMT in RQ3 is correlating with RMS theory, the sub-characteristics described by Rösiö et al. (2019) have been assessed through a tripartite evaluation. This enabled the possibility to answer RQ4. Each of the sub-characteristics have been marked with an "X" whether they have a direct correlation, indirect correlation or if there is no evidential correlation between the sub characteristics and the DMT (Table 5). The definition of the formulations is as follows:

- *Direct correlation (DC)* – sub-characteristics of a production system that the DMT is directly supporting the function of. An attribute of the tool, i.e. input, output, or function, is making this sub-characteristic possible.
- *Indirect correlation (IC)* – sub-characteristics of a production system that the DMT is indirectly supporting. In other words, the DMT is working under the assumption that these characteristics exist in the production system already in order to function properly.
- *No evidential correlation (NC)* - non relevant or no evidential correlation between the sub-characteristic and DMT. For instance, the tool is completely disconnected from how the company is moving products between stations and between assembly lines.

Table 5 - RMS and DMT correlation, modified from Rösiö et al. (2019).

Characteristic	Sub-characteristic	DC	IC	NC	Evaluation
Scalability	Machinery		X		The decision-making tool (DMT) considers a line where machinery can be added or removed effortlessly from the assembly line.
	Shifts and workers	X			The DMT calculates the required number of workers based on the demand.
	Lead time	X			The DMT can indicate the feasible increase in production volume and hence lead time.
	Line Balancing	X			The line balancing is a direct output of the DMT.
	Task time	X			The DMT considers task times as a direct input.
	Utilization of space	X			The DMT considers the space required for the assembly line as an input.
Customization	Tool customization		X		The DMT is directly working under the assumption that the same tools can be used for several products.
	Controller customization			X	No direct correlation to extending the control software to new products.
	Operation customization		X		The DMT does not directly support running different operations within the same station, although it requires a degree of customization as a prerequisite for smooth mixed-model line balancing.
	System customization	X			The DMT provides inputs for the required capacity for new demands.
	Size customization			X	The DMT is not related to the dimensions of products.
	Color customization			X	The DMT is not related to the visual appearance of products.
	Design customization			X	The DMT is not related to the customization of products
Convertibility	Software convertibility			X	The DMT is not related to reprogramming of existing software.
	Increment of conversion	X			The DMT supports producing new product variants among current products.
	Routing			X	The DMT is not correlated with material handling

	convertibility				outside the assembly line.
	Line routing configurability	X			The DMT supports parallel stations within the same line.
	Replicated machines		X		The DMT works in a setup where it is possible to replicate machines to increase production capacity
	Fixture convertibility		X		The DMT considers neglectable setup time for fixtures, assuming that the setup of the assembly line to the new variants setting is achieved automatically.
	Tool convertibility		X		The DMT considers neglectable setup time for tools, assuming that the setup of the assembly line to the new variants setting is achieved automatically.
	Multi-directional			X	The DMT solely focuses on operations, not other activities between stations and between assembly lines.
	Asynchronous motion			X	The DMT solely focuses on operations, not other activities between stations and between assembly lines.
	Level of automation			X	The DMT is not related to the system's ability to include a high level of automation.
Modularity	Tool modularity		X		The DMT is working under the assumption that tools are either modular or product variants share the same tools.
	Workstation modularity		X		The DMT is working under the assumption that workstations are either modular or product variants share the same workstations.
	Fixture modularity		X		The DMT is working under the assumption that fixtures are either modular or product variants share the same fixtures.
	Operation sequence	X			The DMT's main purpose is to investigate the ability to produce two or more product variants in the same line, and then structure operations sequence to fit all variants within the same product family.
	Component sharing			X	Due to that the DMT has been designed to cope with single-model and mixed-model line balancing, it is only working for products within the same product family (otherwise, setup time would be required to include).
	Component swapping			X	The DMT does not depend on which components the product variants consist of, but solely on the operations required to produce those.
	Cut to fit			X	The DMT does not depend on which modules are used in the product variants.
	Bus modularity			X	The DMT does not depend on which modules are used in the product variants.
Integrability	Tool integrability		X		The DMT is working under the assumption that integration of new tools in existing machines is possible.
	Fixture integrability*		X		The DMT is operating on the assumption that different fixtures will be integrated with existing machines.
	Control software			X	Software integrability is not affected nor affecting the DMT.
	Information handling integrability		X		The DMT can easily be integrated with similar tools within managerial and financial analysis, if those are created in Microsoft Excel (or in other compatible software).

Diagnosability	Poka yoke			X	The DMT does not affect, nor is affected by the capability to detect the usage of correct tool and components for the product variants.
	Information board	X			The DMT is providing the user with information regarding which production task sequence to follow.
	Traceability			X	The DMT is not directly connected to any traceability information or diagnosability tools.
	Quality assurance			X	The DMT does not take quality changes into consideration.

* Sub-characteristic added by authors of this thesis.

To illustrate the overarching connection between RMS characteristics and the decision-making tool, the following table was created (Table 6). The direct connections are to be reckoned as significant for the DMT, and thus their numerical value is worth significantly more than the indirect correlations.

Table 6 - RMS characteristics and DMT correlation summary

Characteristic	**Direct correlation**	**Indirect correlation**	**No correlation**
Scalability	5	1	-
Customization	1	2	4
Convertibility	2	3	5
Modularity	1	3	4
Integrability	-	2	1
Diagnosability	1	-	3
Total	**10**	**11**	**17**

In order to further describe the evaluation between RMS sub-characteristics and the DMT, the following paragraphs have been created.

Scalability, the evaluation showed a direct correlation with 5 out of 6 sub-characteristics within scalability. These are primarily related to the system's ability to adjust production capacity. For instance, the line balancing module in the decision-making tool calculates the required number of workers or stations based on the demand and available working time. This established a direct correlation to the sub-characteristics line balancing, shift and workers, lead time and line balancing. Furthermore, the investment perspective of the decision-making tool considers rent of the area as a factor to calculate investment costs, which is related to the utilization of space. Only a single sub-characteristic was classified as having an indirect correlation to the DMT, this covered the possibility to add machines easily. This inherent ability of the production system is a prerequisite in order to conduct line balancing, as otherwise the MMALB would not be possible. Hence it was recognized as having an indirect correlation to the DMT.

Customization, the DMT did not indicate any strong overall connections to the RMS sub-characteristics within customization. Primarily since there are no correlations between the DMT and product features such as size, color, and design. Also, the DMT is not connected to control customization and software that is used to control the production process. However, two sub-characteristics were found to have indirect correlations with the DMT. One of these regards the tool's ability to arrange processes within the stations, i.e. tool customization. This was identified as an indirect correlation since the mixed-model assembly line assumes that the same tools can be used to produce different product variants. Therefore this is recognized as a major part of the DMT's assumption. The second sub-characteristic with an indirect correlation to the DMT involves the operation customization required when running different processes within the same station. Lastly, the only direct correlation identified involves system customization. This since the tool evaluates the decision of introducing a new product to the existing production system, which is the core of this sub-characteristic.

Convertibility, only two sub-categories within convertibility were recognized as having a direct connection with the tool. These regards incremental of conversion and line routing configurability. The DMT was designed in order to test the capability of producing a new product variant in an already existing production line which is a clear connection to the sub-characteristic incremental of conversion. As for the line routing, since the DMT is supporting parallel stations within the same assembly line, a direct connection was recognized. Furthermore, the sub-characteristics fixture convertibility and tool convertibility were defined as having an indirect correlation with the tool's attributes. This indirect correlation was identified since the basic assumption of the DMT is to neglect the setup time required when changing between product variants. Furthermore, half of the sub-characteristics were classified as having no evidential correlation to the DMT. This due to the fact that the DMT focuses on an assembly line level and is not connected to the routing of AVGs or the programming of other production software. Similarly, the sub-characteristics multidirectional and asynchronous motion were identified as not relevant since the material handling equipment of the line is not related to the DMT. Lastly, since the DMT works in a reconfigurable context without considering the level of automation in the assembly line, this sub-characteristic was evaluated as having no evidential correlation to the tool.

*Modularity***,** in total three of the sub-characteristics were connected to having an indirect correlation with the DMT. These regard tool, workstation, and fixture modularity. The identified connection is that the DMT is working under the assumption that physical aspects of a production system are modular, as it otherwise would not be possible to efficiently produce product variants within the same assembly lines without extensive setup time. And since the DMT does not take account for setup-time, these sub-characteristics fit under the indirect correlation. The sub-characteristic operation sequence was the only part matched with a direct correlation. This since the DMT's main purpose is to investigate the ability to produce two or more product variants in the same line, and then structure operations sequence to fit all variants within the same product family. Lastly, four sub-characteristics within modularity were identified as having no correlation with the DMT. These sub-characteristics were formulated from a product development perspective, which is not related to the DMT since it solely focused on production systems.

Integrability, two of the sub-characteristics within integrability were identified as having an indirect correlation with the DMT. These sub-characteristics cover tool integrability and information handling integrability. The former since the DMT is working under the assumption that integration of new tools in existing machines is possible, otherwise a mixed-model assembly line balancing procedure would not be possible. This would automatically result in the requirement of purchasing a completely new assembly line, including tools and fixtures. The latter sub-characteristic, i.e. information handling integrability, was recognized as having an indirect correlation due to the DMT's ability to easily be integrated with other Microsoft Excel files. The integration can, for instance, regard tools within managerial and financial analytics. The only sub-characteristic identified as neither being affected by nor affecting the DMT was control software, which involves the capability to integrate already existing control software into new tools, fixtures, and machines. The non-existent correlation to the DMT was recognized since the control software is focusing on a technical level and not on a planning level which the focal point in the DMT. Furthermore, the sub-characteristic fixture integrability was added to the analysis. This sub-characteristic was included in order to establish coherence in the evaluation table. And since the fixture was explicitly in focus in other RMS characteristics such as modularity and convertibility, it was necessary to consider it as a sub-characteristic of integrability as well.

Diagnosability includes a total of four sub-characteristics, whereas three of those (Poka yoke, traceability, and quality assurance) have been recognized as having no correlation with the DMT. Poka yoka and traceability requires a direct software connection to tools, fixtures, and machines in the production system. Since the DMT was designed in Microsoft Excel, this might be theoretically possible. However, as the software used to enable Poka yoke and traceability probably is more sophisticated than Microsoft Excel, and therefore the combability is not obvious. Hence, these sub-characteristics this was neither addressed as a precondition nor a requirement for the DMT. Quality is an aspect the tool does not take quality changes into consideration. Instead, the DMT works under the assumption that quality is not affected regardless if the new product(s) are produced in combined or separate assembly lines. Even though the input OEE-target includes a quality aspect, which entitles that it is not entirely neglected in the model, the user cannot change the quality output on a single alternative. Therefor the quality assurance was recognized as having no direct correlation to the DMT. However, the analysis also indicates that one sub-characteristic has a direct correlation to the DMT, i.e. the information board. This was recognized since the tool is providing the user with the information about which tasks are to be performed at each station, but also which task sequence is the most beneficial to follow in each station. However, this is solely possible to translate to an information board if the production system has an inherent ability to display the upcoming operation on the focal machine or assembly line.

With the outputs gained from Table 6, it is possible to recognize that the strongest correlation between RMS and the DMT regards the characteristic scalability. This might be regarded as a realistic result, primarily since the DMT is working on a system level, as described by Napoleone (2018), and thereby the assembly line is in focus within scalability. Apart from scalability, the RMS characteristic convertibility was also found to have a noteworthy linkage to the tool. This since it was the second-highest characteristic with a direct correlation to the DMT. Similar to the argument for scalability, this is from a theoretical standpoint a realistic result. Because convertibility is also connected to the system level of RMS. This noteworthy correlation between DMT and the characteristics scalability and convertibility has been illustrated in Figure 21 through the darker shade of grey.

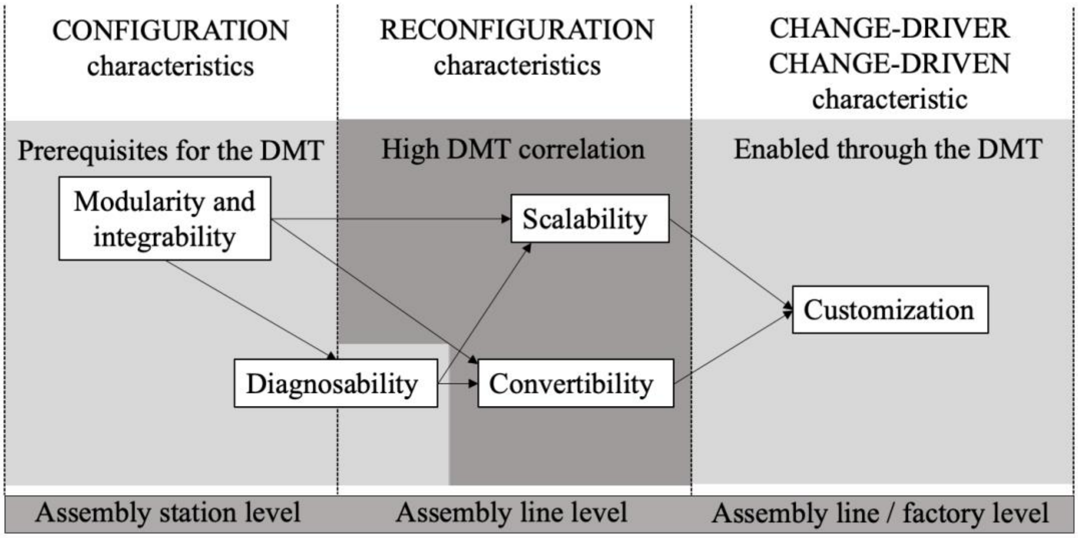

Figure 21 - RMS characteristic and DMT connection, based on Napoleone et al. (2018)

Furthermore, the characteristics modularity, integrability and diagnosability were found to a fairly low overarching correlation with the DMT. This since they only had either zero or one sub-characteristic with a direct correlation to the DMT. Given the fact that those characteristics are, according to Napoleone (2018), within the workstation level, the fact that those are more related to indirect correlation can be regarded as reasonable. Because, these characteristics are a prerequisite for the scalability and convertibility, hence they are also a prerequisite for the DMT. However, having scalability and convertibility within the system level can also facilitate developing customisation within the system/factory level, which is indicated by the fairly non-existent connection between the DMT and this particular characteristic, i.e. customization.

In summary, the DMT is working in a setup where modularity and integrability are within the workstation level, i.e. machines and cells, hence they are prerequisites for the DMT to work, rather than input, outputs, or attributes of the DMT. Neglection of these characteristics should occur, because they support the scalability and convertibility within the system level, i.e. the assembly lines, which are the characteristics directly correlated to the DMT. Similarly, scalability and convertibility in a system-level is a prerequisite for having customization at the factory level. This indicates that the model is supporting the customization at the assembly line/factory level, which in turn affects the company's overarching ability to deal with fluctuations in the demands and an increased product introduction rate. Through this support, the DMT can be recognized as a way to facilitate companies' transition towards reconfigurable manufacturing systems.

Even though the analysis between the DMT and RMS sub-characteristics can be recognized as a valid evaluation method, it has some downsides and limitations. For instance, the amount and formulation of the sub-characteristics presented by Rösiö et al. (2019) might have a major impact when measuring the sum of correlations. Thereby, any potential imbalance amongst sub-characteristics will affect the measuring. These imbalances can, for instance, regard a higher amount of sub-characteristics related to a certain RMS characteristic, causing a probable higher numerical value. Therefore, the results should not be regarded as a numerical result, but rather as a way to establish a connection between RMS and the DMT on a principal level. Issues regarding unbalanced sub-characteristics were recognized. For instance, several sub-characteristics are focusing on AGVs. But since the DMT is solely limiting to assembly lines, and not the surrounding production system, the numerical result is highly affected for the entire characteristic. Similarly, several sub-characteristics such as component swapping, cut to fit and bus modularity were more closely related to product configuration rather than production systems. This created a similar effect on the numerical result as the aforementioned issue. These issues might have caused limitations to the conclusions drawn in this thesis, however the results can still be recognized as valid due to the theoretical coherence found in the analysis.

6.2 Discussion of method

This thesis was carried out with a structure primarily focusing on exploring and explaining. These attributes correspond to a qualitative research approach (Leedy et al., 2019). The qualitative approach is namely characterized as having flexible guidelines which were necessary since the outcomes were not predetermined, but instead explorative. Choosing this approach helped to answer research questions in a field where a unanimous theoretical foundation was lacking. Literature studies were carried out as a means to answer the first and second research question, whilst also setting the theoretical foundation for answering the fourth research question. The literature studies followed a modified five step procedure, originally developed by Booth et al. (2016). Extensive literature studies were conducted in three areas: RMS, line balancing and assembly line investment costs. These covered broad areas, as a means to investigate all possible options for developing and evaluating the decision-making tool. Following a structured literature study procedure in several fields was crucial given that the study's purpose was partly explorative and focused the combination of several theoretical fields which have not been studied simultaneously before. However, covering broad theoretical areas also brough implications. For instance, due to line balancing being a significantly broad area with a substantial amount of potential techniques and algorithms, there was a possibility that not all of these were identified in the literature study. As a means to minimize this issue, several searches within each literature study were conducted.

In order to develop the decision-making tool, and thereby create the possibility to answer the third and fourth research question, a single case study was carried out. However, as the case study was conducted in an industry specific context, transferability was restricted. To battle this issue, the decision-making tool was thoroughly explained in order to grant readers the possibility of deciding whether it can be applied in their area, i.e. thick description (Lincoln & Guba, 1985). Furthermore, to increase credibility, data triangulation was implemented in the case study. This included document studies, interviews and focus group. The document studies were carried out by the focal company sending the documents electronically, which were then studied carefully. However, the case company calculated investments through a rather complicated procedure, which did not fit with the scope of when to use the tool, as it required a substantial amount of information. Hence, a complication occurred regarding using the information gained from the company and trying to adopt these into the model to fit with the identified theory. This forced us to rely more on the theoretically identified solutions of calculating investments.

Interviews were carried out in the form of bi-weekly meetings with a production engineer at the case company. Limiting the interviews to a single individual might have delimited the credibility of the collected data. However, the data gathered from interviews was mainly used to facilitate a close connection to industry, hence these results can still be recognized as credible. Conducting interviews with other employees from a wide set of departments, would enhance the probability of developing a decision-making tool from a systems perspective. Though, instead of conducting separate interviews, a focus group was carried out as a means to facilitate discussion and gather decision-making tool feedback. The participants in the focus group were chosen based on their position in the case company, ensuring the tool's validity by collecting feedback from several departments. This was especially important since the bi-weekly interviews only were conducted with an employee from the assembly engineering department, and not from the financial department. Unfortunately, due to time limits, only a single focus group was carried out. Conducting several focus groups, across multiple companies would enhance credibility and transferability for both the decision-making tool and the thesis.

The validation and testing process of the decision-making tool was based on Caine & Robson's (1993) structure. This procedure was chosen since it focuses on spreadsheet models. By following each step thoroughly, and thereby continuously testing the decision-making tool, the accurateness was improved. However, the final step, consisting of inserting case company data in the DMT and comparing those to the previous calculations made by the case company, was solely conducted once at the case company. This due to the lack of realistic cases and relevant data. Similarly, due to lack of resources and time, the decision-making tool was only tested in a single-case study. By only testing the decision-making tool in a single setting, the generalizability of the thesis and decision-making tool can be considered limited but at the same time offering the possibility to test the DMT's functionality and usability.

7 Conclusions

The seventh chapter presents the industrial and academic contribution, thesis limitations and suggestions of future research.

7.1 Industrial contribution

In time with RMS becoming more frequently used in companies, given its ability to deal with future customers' higher demand of customization, the applicability of mixed-model assembly line balancing is starting to excel. Simultaneously, in line with an increased product introduction rate, a new kind of investment decision taken during the early stages of new product development has increased in frequency. These decisions regard whether to produce a new product variant in an already existing production line or invest in a new line. By developing a decision-making tool that focuses on investment decisions and mixed-model line balancing simultaneously, a more well-informed decision including all the aforementioned issues and factors can be taken. Since the decision-making tool has been developed specifically with RMS in mind, the transition from DMS and FMS to RMS can be facilitated in an easier way. Because, by using the decision-making tool, companies are able to solve a major issue frequently stumbled across during the early phases of new product development, namely how and where to produce upcoming products. For the case company, the decision-making tool is directly supporting the case company's project regarding a change from current dedicated and flexible manufacturing systems towards RMS. This transition would boost the company's ability to respond to changes in the market and customers demand while keeping high level of optimization to guarantee competitive prices. Besides from being able to use the DMT to enhance production decisions, it also helps the case company to select the most effective line balancing technique for both mixed-model assembly lines and single-model assembly lines. This will further streamline the production of both current and upcoming products.

Furthermore, due to the decision-making tool's ability to investigate the compatibility of producing two (or several) products in the same line, whilst taking potential investment costs into consideration, the model is not fixed on a specific company situation. Thus, the decision-making tool can be used both when the user's company has a low level of RMS, but also when having a fully developed RMS. In the latter, the system will most likely already be prepared for upscaling, and thereby the fixed investment costs covering buildings and land can be neglected. By designing the model to be both scalable and modular, it is possible to ensure a wider industrial application. For instance, the line balancing module is capable of coping with up to 50 task input values, and the user simply has to insert the number of tasks used in their case, without having to adjust anything in the decision-making tool. Also, the investment module is capable of adjusting the names and classification of investment costs, hence adaptable for a company specific situation. Lastly, by using a spreadsheet software, such as Microsoft Excel, the applicability in a wider industry can be achieved since this software is globally well-known software which requires minimum pre-existing knowledge before using it. Lastly, the DMT can be utilized in the early stages of the product development process and provide insights about the required infrastructure of a production system and the expected investment costs.

7.2 Academic contribution

This thesis has bridged the gap regarding which line balancing-solving techniques are possible to apply in an RMS milieu. This was achieved by exploring a wide theoretical area and then compiling and classifying different line balancing-solving techniques. Correspondingly, the literature review exposed a theoretical gap regarding which investment cost can be considered vital for new assembly lines as a consequence from new product introductions. By investigating and combining the theoretical findings and case study findings, this gap has been bridged, resulting in a new classification of investment costs.

Furthermore, the thesis also investigated and analysed the relation between RMS characteristics and the developed decision-making tool. Through this, the thesis contributed to academia by developing a procedure to estimate the connection of production development tools and RMS. This procedure, i.e. the outcomes of table Table 5 and Table 6, can be utilized in a wide arrange of situations and enables a possibility to support companies' transition towards RMS, as they will easily have the capability to compete with other companies. Similarly, by connecting previous research by Rösiö (2019) and Napoleone (2018), a further step into creating a unanimous theoretical field within RMS has been taken. This is essential since the RMS theory currently is very wide and does not have a generally accepted theoretical foundation, which not only complicated this research, but most likely previous research as well.

7.3 Limitations and future research

In this thesis, by adapting a previously designed line balancing tool to fit the characteristics of RMS, a step to ease companies' transition towards RMS has been taken. An investigation covering the potential upgrade of other production development tools, such as VSM and SMED, can be accomplished given that the results of this thesis have proven it possible. Consequently, the suggested evaluation method can be applied for anchoring the RMS connection in future production development tools as well. However, in line with an extension of RMS theory, the sub-characteristics might be developed to provide a more accurate description of RMS. Hence research to enhance the sub-characteristics might be necessary as well. Future research is also needed to reformulate the sub-characteristic presented by Rösiö et al. (2019) to fit with the works of Napoleone et al. (2018). Adapting the sub-characteristics to fit with the RMS level theory is necessary to fully establish a common framework for evaluating production development tools.

Further developing the decision-making tool might include testing the possibility to add certain production order sequencing restraints, in order to provide an even more accurate result. However, as this is hugely dependent on accurate input data, it was not included in this thesis. Also, the usability of the model can be altered into being a complete line balancing tool specifically for everyday usage, rather than decision-making tool. Enhancing the decision-making tool’s accuracy by adding further line balancing techniques might also be of future significance. For instance, adding the heuristic method *Ranked Positional Weight* might provide the user with additional possibilities for maximising line balancing KPIs. Similarly, further development of the DMT might include adding more sophisticated line balancing KPIs such as flexibility of staff, process planning, market requirements and planned order execution time.

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9 Appendices

9.1 Appendix 1 – Focus group questioning route

Opening questions:

- What is your name?
- Which area within the case company are you working in?

Introductory:

- How do you currently work with line balancing or investment decisions in your job?

Transition:

- Have you previously faced issues with line balancing or investments decision when deciding how a new product should be produced?
- Have you any previous experience with a similar tool?

Key questions:

- Were the instructions clear?
- Was the input data easy to insert?
- Is the input data possible to gather?

- Was the model easy to use?
- Which part was easier to use?
- Which part was harder to use?

- What did you think of the black-box model within this type of tool?
- What did you think of the visual appearance of the tool?
- Do you think the level of complexity is suitable?

- Is the investment calculation relevant given the company's current way of estimating investments?
- How can the tool be integrated with other financial or planning excel-files you currently are using?

- Do you think you be able to use the model?
    - If not, why?
    - If yes, approximately how often?
- Do you think the tool can be used in other subsidiaries of the case company?
- Do you think you will be able to use the tool to enhance your decision making?

Ending questions:

- Were there any parts you did not understand?
- What do you reckon the model is lacking?
- What do you reckon the model is having that you did not expect beforehand?
- How can the line balancing module be improved?
- How can the investment calculation be improved?
- How can the tool overall be improved?

9.2 Appendix 2 – DMT excerpts

9.2.1 Front sheet excerpt

Decision making tool

Front sheet

Created by: Mohamed Abdelmageed & Filip Skärin

(1) General decision making tool logic

The tool has been created in order to ease the decision making regarding whether to produce an upcoming product in an already existing assembly line, or to invest in new assembly line. The general idea is to use the tool before the industrialization phase of the product, even though it can be used in a wide arrange of settings. The tool is designed with a color code and the user is expected to follow the steps highlighted above in order for the tool to work.

The creators have knowingly decreased the user complexity by simplifying the spreadsheets related to input and results. Although, as a means to keep a high level of functionality, the tool works under with black-box principle. Meaning that the most complex calculations done in the tool is accomplished automatically. These spreadsheets are coloured in orange and should preferably not be altered or changed as a way to avoid risking the tool's functionality.

The tool is conducting mixed-model assembly line balancing for calculating the KPIs when producing the products in the same line, and single-model assembly line balancing for calculating the KPIs when producing the products in separate lines. In the former, two ways of calculating the combined task time is used: Max Task Time and Weighted Average Task Time. Once the new task times have been calculated, the tool automatically performs line balancing by using the priority rule Longest operation time. For the single-model assembly line balancing, the tool is using four different priority rules: Longest operation time, Most following tasks, Shortest operation time and Least following tasks (currently only LOT is displayed, the remaining sheets are hidden). Once the line balancing parts have been calculated, the balance losses is converted into an annual cost which is then compared with the potential investment costs for each alternative (i.e. either combined production within the existing assembly line or separate production lines). By adding these costs together, it is possible to gain a total cost for each alternative. The tool then recommends the alternative with the lowest total costs.

(2) Step and task linkage

Steps	Responsible	Sheet	Task
Step 1	User	LB Input data	Insert product data
Step 2	User	LB Input data	Insert general data
Step 3	User	Investment Input Data	Insert investment data
Step 4	Program	Combine ABC	Calculate task times for combined production
Step 5	Program	LB WATT ABC	Conduct mixed-model line balancing using Weighted Average Task Time
Step 6	Program	LB MAX ABC	Conduct mixed-model line balancing using Max Task Time
Step 7	Program	LB Line A	Conduct single-model line balancing for product A using four different priority rules
Step 8	Program	LB Line B	Conduct single-model line balancing for product B using four different priority rules
Step 9	Program	LB Line C	Conduct single-model line balancing for product C using four different priority rules (if feasible)
Step 10	Program	MC	Perform Monte Carlo simulation for investment costs
Step 11	Program	Detailed results	Compare costs for both alternatives and all priority rules
Step 12	Program	Result	Present comparison between best alternative and technique
Step 13	User	Result	Analyse output

9.2.2 Front sheet excerpt

(3) Input assumptions

- Task times are calculated beforehand by the user.
- No setup time is required when producing several product in the same line
- Task times are including times for walking, moving the product and preparing the next task
- All parameters in the model are assumed to be deterministic.
- Task times are fixed, unless changed by user.
- There is not a fixed set of stations, this is calculated by the decision making tool.
- The total time of a task cannot exceed the required cycle time.
  If a task is exceeding the required cycle time, the user must divide the task into two or more tasks in order for the tool conduct the line balancing.
- The assembly line is of a serial line-layout kind (not U-shaped line)
- The input parameters are correct, for instance, the predecessors must follow a logic and true diagram.
- Each station needs exactly one worker.
- Fixed costs are based on the entire investment costs, i.e. no depreciations are calculated in the model.
  If depreciation should be included, the user has to take this into consideration when inserting input values.

(4) Update logic

The tool was designed to be flexible and easy to use. Microsoft Excel was chosen since it requires minimum knowledge about software and its functionality from the user. The majority of input data has been designed and labelled according to fit a wide arrange of companies/users. In the need of updating, please ensure to check the precedents and dependents of cells/formulas in order to avoid collateral damage. However, the tool should be regarded as working with a black-box principle, meaning that the spreadsheets coloured in orange should not be visible for the average user, but only for the designated administrator at the company. As a means to avoid decreasing the tool's functional, the creators suggest to create an in-house rule which covers that novelty users should not alter or change any formulas in sheets coloured orange due to the aforementioned statement regarding connected cells/formulas.

For questions regarding the tool, contact:

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Filip Skärin	filipskarin@hotmail.com	+46 76 104 58 34

End of sheet

9.2.3 Line balancing input data excerpt

Line balancing input data

Product A				
Task name	Task code	Task time (s)	Predecessor task	Number of following tasks
ST040	A	185	--	7
ST041	B	245	A	6
ST042	C	126	B	5
ST043	D	333	C,A	4
ST044	E	188	D	3
ST045	F	249	E	2
ST046	G	100	F	1
ST047	H	300	G	0

Product B				
Task name	Task code	Task time (s)	Predecessor task	Number of following tasks
ST040	A	180	--	7
ST041	B	243	A	6
ST042	C	181	B	5
ST043	D	301	C	4
ST044	E	100	D	3
ST045	F	120	E	2
ST046	G	242	F	1
ST047	H	241	G	0

Product C				
Task name	Task code	Task time (s)	Predecessor task	Number of following
ST040	A	0	--	7
ST041	B	0	A	6
ST042	C	0	B	5
ST043	D	0	C	4
ST044	E	0	D	3
ST045	F	0	E	2
ST046	G	0	F	1
ST047	H	0	G	0

	Yearly volume product A	Yearly volume product B	Yearly volume product C
Demand per year	7000	11000	79999
Weighted demand	0,1	0,1	0,8
Required cycletime	879	560	77

Total production time per operator (hrs/year)	1900
OEE target	90%
Total demand per year	97999
Actual available production time (hrs/year)	1710
Demand per hour	57
Required cycletime for combined line (s)	63

Input instructions:
- Always put task times in seconds (s)
- Ensure to insert all values to product A
- Insert task time = 0 if not applicable for certain product (e.g. if task AB140 has task time of 40 s for Product A & B, but isn't part of assembly of Product C, put 0 for Product C).
- Use same name for tasks for all products.
- Input only values where highlighted with BLUE.

9.2.4 Investment input data excerpt

Investment input data

Investment in new line

Fixed costs	Expected	St.dev
Task-related investment costs		
Machines	200 000 kr	10%
Fixtures	100 000 kr	10%
Tools	100 000 kr	10%
Equipment	100 000 kr	10%
Spare parts	100 000 kr	9%
Other		
Workstation investment costs		
Chairs	200 000 kr	10%
Mats	100 000 kr	10%
Workbenches	100 000 kr	10%
Other		
Intangible costs		
Labour costs		
Education	50 000 kr	10%
Salaries	50 000 kr	10%
Other	50 000 kr	10%
Floor space costs		
Construction	20 000 kr	10%
Engineering	2 000 kr	10%
Rent	2 000 kr	10%
Hearing & energy	2 000 kr	10%
Other	2 000 kr	10%
Grand total	1 178 000 kr	9,94%

Upgrade of existing line

Fixed costs	Expected	St.dev
Task-related investment costs		
Machines	200 000 kr	10%
Fixtures	100 000 kr	10%
Tools	100 000 kr	10%
Equipment	100 000 kr	10%
Spare parts	100 000 kr	9%
Other		
Workstation investment costs		
Chairs	200 000 kr	10%
Mats	100 000 kr	10%
Workbenches	100 000 kr	10%
Other		
Intangible costs		
Labour costs		
Education	50 000 kr	10%
Salaries	50 000 kr	10%
Other	50 000 kr	10%
Floor space costs		
Construction	20 000 kr	10%
Engineering	2 000 kr	10%
Rent	2 000 kr	10%
Hearing & energy	2 000 kr	10%
Other	2 000 kr	10%
Grand total	1 178 000 kr	9,94%

Input instructions:

- In this sheet the user is to insert investment costs for the two alternatives. The left alternative is summarizing the expected (+ standard deviation) costs for investing in a new line). The right alternative is summarizing the expected (+ standard deviation) costs for upgrading the existing production line.

- Input only values where highlighted in BLUE.

- Always put investment costs in same currency.

- If a cost is not applicable in your case, insert value of 0.

- Standard deviations are put in same currency as expected cost. If standard deviation is not applicable, insert a value of 0.

- Only insert investment costs associated with the new product. For instance, old investment costs for the existing product is not considered.

- If an investment cost post in you calculations aren't included in this template, add this to the appropriate "other" cost.

- Direct investments preferably calculated on a yearly basis if concerning considerable investments.

- Operator costs are only higlighting the annual cost per operator, this number will be muliplied with the number of stations later on in the tool

- Employee costs for material handlers, measurement technicians and other are only inserted if the user recognizes this as necessary and covers the entire annual costs for these employees (these costs will not multiplied with the number of stations).

9.2.5 Combining of task times for MMLB excerpt

In this sheet the tool is calculating the *Weighted task times* and *Max task times* based on the input from the sheet "LB Input Data". The predecessor tasks for all products are also calculated. The output in the left column (MMLB Product ABC, column B-E) is the new input for the sheets "LB Line ABC" and "LB Line MAX ABC".

The *Weighted task times* are calculated by summarizing the product of multiplying the weighted demand with the task time for all products.
The *Max task times* is simply comparing the task times for all product regarding the task, and select the maximum of those.

MMLB Product ABC

Task code	Weighted average task time	Max task time	Precedessor task
A	33	185	--
B	45	245	A
C	29	181	B
D	58	333	C,A, C
E	25	188	D
F	31	249	E
G	34	242	F
H	48	300	G
		0	
		0	
		0	
		0	
		0	
		0	
		0	
		0	
		0	
		0	
		0	
		0	
		0	
		0	
		0	
		0	
		0	
		0	
		0	
		0	
		0	

MMLB Product ABC

Task name	Task code	Task time (s) A	Task time (s) B	Task time (s) C
ST040	A	185	180	0
ST041	B	245	243	0
ST042	C	126	181	0
ST043	D	333	301	0
ST044	E	188	100	0
ST045	F	249	120	0
ST046	G	100	242	0
ST047	H	300	241	0

Product A

Task name	Task code	Task time (s)	Predecessor task
ST040	A	185	--
ST041	B	245	A
ST042	C	126	B
ST043	D	333	C,A
ST044	E	188	D
ST045	F	249	E
ST046	G	100	F
ST047	H	300	G

Product B

Task name	Task code	Task time (s)	Predecessor task
ST040	A	180	--
ST041	B	243	A
ST042	C	181	B
ST043	D	301	C
ST044	E	100	D
ST045	F	120	E
ST046	G	242	F
ST047	H	241	G

Product C

Task name	Task code	Task time (s)	Predecessor task
ST040	A	0	--
ST041	B	0	A
ST042	C	0	B
ST043	D	0	C
ST044	E	0	D
ST045	F	0	E
ST046	G	0	F
ST047	H	0	G

9.2.6 MMLB Line ABC WATT excerpt

MMLB Line ABC — Cycle time(s): 63

Weighted Average Task Time

Lookup critetion	Task name	Task code	WATT	Predecessor task
33	ST040	A	33	--
45	ST041	B	45	A
29	ST042	C	29	B
58	ST043	D	58	C,A, C
25	ST044	E	25	D
31	ST045	F	31	E
34	ST046	G	34	F
48	ST047	H	48	G
0		N/A		
0		N/A		
0		N/A		
0		N/A		
0		N/A		
0		N/A		
0		N/A		
0		N/A		
0		N/A		
0		N/A		
0		N/A		
0		N/A		
0		N/A		
0		N/A		
0		N/A		
0		N/A		
0		N/A		
0		N/A		
0		N/A		
0		N/A		
0		N/A		
0		N/A		
0		N/A		
0		N/A		
0		N/A		
0		N/A		
0		N/A		

WATT	Iteration
33	0
45	1
29	1
58	2
25	1
31	1
34	1
48	1
0	-1
0	-1
0	-1
0	-1
0	-1
0	-1
0	-1
0	-1
0	-1
0	-1
0	-1
0	-1
0	-1
0	-1
0	-1
0	-1
0	-1
0	-1
0	-1
0	-1
0	-1
0	-1
0	-1
0	-1
0	-1
0	-1
0	-1

Selecting the next task	Iteration 1	Iteration 2	Iteration 3	Iteration 4	Iteration 5	Iteration 6	Iteration 7	Iteration 8	Iteration 9
Step 1: Time available	62,82	29,40	18,04	33,50	5,24	38,16	6,91	28,51	14,34
Step 1: Check if iterations are possible	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	No
Step 1: Number of feasible tasks	1	0	0	0	0	1	0	0	N/A
Step 2: (Possible adjusted) time available	63	63	63	63	63	38	63	63	14
Step 2: Station number	1	2	3	4	5	5	6	7	7
Step 3: Activity time	33	45	29	58	25	31	34	48	0
Step 3: Activity name	A	B	C	D	E	F	G	H	N/A

Results	Value
Cycle time (s)	63
Time needed per cycle (s)	304
Theoretical min # of stations	5
Actual # of stations	7
Time allocated per cycle (s)	440
Idle time per cycle (s)	136
Efficiency (%)	69%
Balance delay (%)	31%

INTERATIONS Task	Iteration 1	Iteration 2	Iteration 3	Iteration 4	Iteration 5	Iteration 6	Iteration 7	Iteration 8	Iteration 9	Iteration 10	Iteration 11
ST040	0	-1	-1	-1	-1	-1	-1	-1	-1	-1	-1
ST041	1	0	-1	-1	-1	-1	-1	-1	-1	-1	-1
ST042	1	1	0	-1	-1	-1	-1	-1	-1	-1	-1
ST043	2	1	1	0	-1	-1	-1	-1	-1	-1	-1
ST044	1	1	1	1	0	-1	-1	-1	-1	-1	-1
ST045	1	1	1	1	1	0	-1	-1	-1	-1	-1
ST046	1	1	1	1	1	1	0	-1	-1	-1	-1
ST047	1	1	1	1	1	1	1	0	-1	-1	-1
	-1	-2	-2	-2	-2	-2	-2	-2	-2	-3	-4
	-1	-2	-2	-2	-2	-2	-2	-2	-2	-3	-4
	-1	-2	-2	-2	-2	-2	-2	-2	-2	-3	-4
	-1	-2	-2	-2	-2	-2	-2	-2	-2	-3	-4
	-1	-2	-2	-2	-2	-2	-2	-2	-2	-3	-4
	-1	-2	-2	-2	-2	-2	-2	-2	-2	-3	-4
	-1	-2	-2	-2	-2	-2	-2	-2	-2	-3	-4
	-1	-2	-2	-2	-2	-2	-2	-2	-2	-3	-4
	-1	-2	-2	-2	-2	-2	-2	-2	-2	-3	-4

9.2.7 MMLB Line ABC MTT excerpt

MMLB Line ABC Cycle time(s) 63

Max task time

Lookup critetion	Task name	Task code	Max task time	Predecessor task
185	ST040	A	185	–
245	ST041	B	245	A
181	ST042	C	181	B
333	ST043	D	333	C,A, C
188	ST044	E	188	D
249	ST045	F	249	E
242	ST046	G	242	F
300	ST047	H	300	G
0		N/A	0	
0		N/A	0	
0		N/A	0	
0		N/A	0	
0		N/A	0	
0		N/A	0	
0		N/A	0	
0		N/A	0	
0		N/A	0	
0		N/A	0	
0		N/A	0	
0		N/A	0	
0		N/A	0	
0		N/A	0	
0		N/A	0	
0		N/A	0	
0		N/A	0	
0		N/A	0	
0		N/A	0	
0		N/A	0	
0		N/A	0	
0		N/A	0	
0		N/A	0	
0		N/A	0	

MTT	Iteration
185	0
245	1
181	1
333	2
188	1
249	1
242	1
300	1
0	-1
0	-1
0	-1
0	-1
0	-1
0	-1
0	-1
0	-1
0	-1
0	-1
0	-1
0	-1
0	-1
0	-1
0	-1
0	-1
0	-1
0	-1
0	-1
0	-1
0	-1
0	-1
0	-1
0	-1

Selecting the next task	Iteration 1	Iteration 2	Iteration 3	Iteration 4	Iteration 5	Iteration 6	Iteration 7
Step 1: Time available	63	63	63	63	63	63	63
Step 1: Check if iterations are possible	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Step 1: Number of feasible tasks	0	0	0	0	0	0	0
Step 2: (Possible adjusted) time available	63	63	63	63	63	63	63
Step 2: Station number	1	2	3	4	5	6	7
Step 3: Activity time	0	0	0	0	0	0	0
Step 3: Activity name	N/A	N/A	N/A	N/A	N/A	N/A	N/A

Results	Value
Cycle time (s)	63
Time needed per cycle (s)	1923
Theoretical min # of	31
Actual # of stations	50
Time allocated per cycle (s)	3141
Idle time per cycle (s)	1218
Efficiency (%)	61%
Balance delay (%)	39%

INTERATIONS Task	Iteration 1	Iteration 2	Iteration 3	Iteration 4	Iteration 5	Iteration 6	Iteration 7	Iteration 8	Iteration 9
ST040	0	0	0	0	0	0	0	0	0
ST041	1	1	1	1	1	1	1	1	1
ST042	1	1	1	1	1	1	1	1	1
ST043	2	2	2	2	2	2	2	2	2
ST044	1	1	1	1	1	1	1	1	1
ST045	1	1	1	1	1	1	1	1	1
ST046	1	1	1	1	1	1	1	1	1
ST047	1	1	1	1	1	1	1	1	1
	-1	-2	-3	-4	-5	-6	-7	-8	-9
	-1	-2	-3	-4	-5	-6	-7	-8	-9
	-1	-2	-3	-4	-5	-6	-7	-8	-9
	-1	-2	-3	-4	-5	-6	-7	-8	-9
	-1	-2	-3	-4	-5	-6	-7	-8	-9
	-1	-2	-3	-4	-5	-6	-7	-8	-9

9.2.8 LB Line A excerpt

Line A Cycle time(s): 879

Lookup criterion	Task name	Task code	Task time	Predecessor task	Prevention code
185	ST040	A	185	--	0,00001
245	ST041	B	245	A	0,00002
126	ST042	C	126	B	0,00003
333	ST043	D	333	C,A	0,00004
188	ST044	E	188	D	0,00005
249	ST045	F	249	E	0,00006
100	ST046	G	100	F	0,00007
300	ST047	H	300	G	0,00008
0	0	N/A			0,00009
0	0	N/A			0,0001
0	0	N/A			0,00011
0	0	N/A			0,00012
0	0	N/A			0,00013
0	0	N/A			0,00014
0	0	N/A			0,00015
0	0	N/A			0,00016
0	0	N/A			0,00017
0	0	N/A			0,00018
0	0	N/A			0,00019
0	0	N/A			0,0002
0	0	N/A			0,00021
0	0	N/A			0,00022
0	0	N/A			0,00023
0	0	N/A			0,00024
0	0	N/A			0,00025
0	0	N/A			0,00026
0	0	N/A			0,00027
0	0	N/A			0,00028
0	0	N/A			0,00029
0	0	N/A			0,0003
0	0	N/A			0,00031
0	0	N/A			0,00032
0	0	N/A			0,00033
0	0	N/A			0,00034
0	0	N/A			0,00035
0	0	N/A			0,00036
0	0	N/A			0,00037
0	0	N/A			0,00038
0	0	N/A			0,00039
0	0	N/A			0,0004
0	0	N/A			0,00041
0	0	N/A			0,00042
0	0	N/A			0,00043
0	0	N/A			0,00044
0	0	N/A			0,00045
0	0	N/A			0,00046
0	0	N/A			0,00047
0	0	N/A			0,00048
0	0	N/A			0,00049
0	0	N/A			0,0005

Changeable Priority rule: 1

Task time	Iteration
185	0
245	1
126	1
333	2
188	1
249	1
100	1
300	1
0	-1
0	-1
0	-1
0	-1
0	-1
0	-1
0	-1
0	-1
0	-1
0	-1
0	-1
0	-1
0	-1
0	-1
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0	-1
0	-1
0	-1
0	-1
0	-1
0	-1
0	-1
0	-1
0	-1
0	-1
0	-1

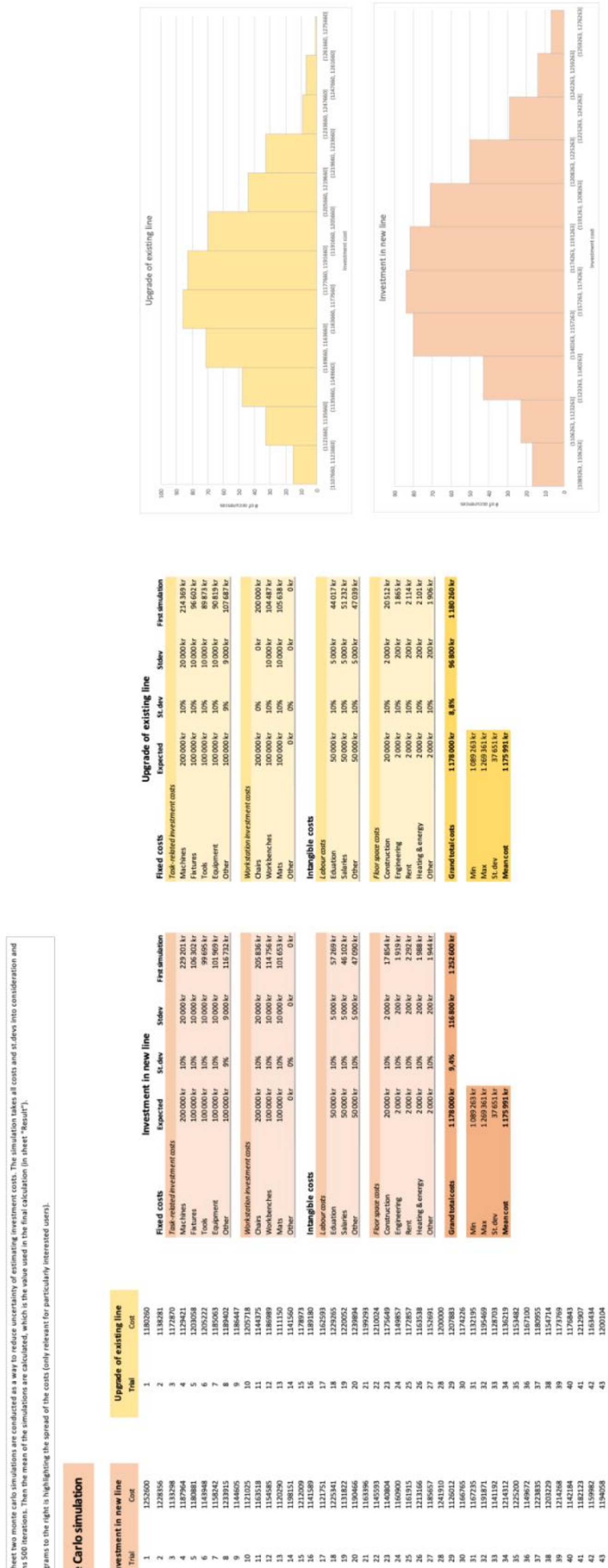
Priority rule			
1 LOT	2 Most following tasks	3 Shortest operation time	4 Least following tasks
185	7	0,005	0,143
245	6	0,004	0,167
126	5	0,008	0,200
333	4	0,003	0,250
188	3	0,005	0,333
249	2	0,004	0,500
100	1	0,010	1,000
300	0	0,003	0,000
0	0	0,000	0,000
0	0	0,000	0,000
0	0	0,000	0,000
0	0	0,000	0,000
0	0	0,000	0,000
0	0	0,000	0,000
0	0	0,000	0,000
0	0	0,000	0,000
0	0	0,000	0,000
0	0	0,000	0,000
0	0	0,000	0,000
0	0	0,000	0,000
0	0	0,000	0,000
0	0	0,000	0,000
0	0	0,000	0,000
0	0	0,000	0,000
0	0	0,000	0,000
0	0	0,000	0,000
0	0	0,000	0,000
0	0	0,000	0,000
0	0	0,000	0,000
0	0	0,000	0,000
0	0	0,000	0,000
0	0	0,000	0,000
0	0	0,000	0,000
0	0	0,000	0,000
0	0	0,000	0,000
0	0	0,000	0,000
0	0	0,000	0,000
0	0	0,000	0,000
0	0	0,000	0,000
0	0	0,000	0,000
0	0	0,000	0,000
0	0	0,000	0,000
0	0	0,000	0,000
0	0	0,000	0,000
0	0	0,000	0,000
0	0	0,000	0,000
0	0	0,000	0,000
0	0	0,000	0,000
0	0	0,000	0,000
0	0	0,000	0,000

Selecting the next task	Iteration 1	Iteration 2	Iteration 3	Iteration 4	Iteration 5	Iteration 6	Iteration 7	Iteration 8
Step 1: Time available	879,43	694,43	449,43	323,43	546,43	358,43	109,43	9,43
Step 1: Check if iterations are possible	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Step 1: Number of feasible tasks	1	1	1	0	1	1	1	0
Step 2: (Possible adjusted) time available	879	694	449	879	546	358	109	879
Step 2: Station number	1	1	1	2	2	2	2	3
Step 3: Lookup citeration	185	245	126	333	188	249	100	300
Step 3: Activity name	A	B	C	D	E	F	G	H
Step 3: Activity time	185	245	126	333	188	249	100	300

Results	Value
Cycle time (s)	879
Throughput time (s)	1726
Theoretical min # of stations	2
Actual # of stations	3
Time allocated per cycle (s)	2638
Idle time per cycle (s)	912
Efficiency (%)	65%
Balance delay (%)	35%

INTERATIONS Task	Iteration 1	Iteration 2	Iteration 3	Iteration 4	Iteration 5	Iteration 6	Iteration 7	Iteration 8	Iteration 9	Iteration 10
ST040	0	-1	-1	-1	-1	-1	-1	-1	-1	-2
ST041	1	0	-1	-1	-1	-1	-1	-1	-1	-2
ST042	1	1	0	-1	-1	-1	-1	-1	-1	-2
ST043	2	1	1	0	-1	-1	-1	-1	-1	-2
ST044	1	1	1	1	0	-1	-1	-1	-1	-2
ST045	1	1	1	1	1	0	-1	-1	-1	-2
ST046	1	1	1	1	1	1	0	-1	-1	-2
ST047	1	1	1	1	1	1	1	0	-1	-2
0	-1	-2	-2	-2	-2	-2	-2	-2	-2	-3
0	-1	-2	-2	-2	-2	-2	-2	-2	-2	-3
0	-1	-2	-2	-2	-2	-2	-2	-2	-2	-3
0	-1	-2	-2	-2	-2	-2	-2	-2	-2	-3
0	-1	-2	-2	-2	-2	-2	-2	-2	-2	-3
0	-1	-2	-2	-2	-2	-2	-2	-2	-2	-3
0	-1	-2	-2	-2	-2	-2	-2	-2	-2	-3
0	-1	-2	-2	-2	-2	-2	-2	-2	-2	-3
0	-1	-2	-2	-2	-2	-2	-2	-2	-2	-3
0	-1	-2	-2	-2	-2	-2	-2	-2	-2	-3
0	-1	-2	-2	-2	-2	-2	-2	-2	-2	-3
0	-1	-2	-2	-2	-2	-2	-2	-2	-2	-3
0	-1	-2	-2	-2	-2	-2	-2	-2	-2	-3
0	-1	-2	-2	-2	-2	-2	-2	-2	-2	-3
0	-1	-2	-2	-2	-2	-2	-2	-2	-2	-3
0	-1	-2	-2	-2	-2	-2	-2	-2	-2	-3
0	-1	-2	-2	-2	-2	-2	-2	-2	-2	-3
0	-1	-2	-2	-2	-2	-2	-2	-2	-2	-3
0	-1	-2	-2	-2	-2	-2	-2	-2	-2	-3
0	-1	-2	-2	-2	-2	-2	-2	-2	-2	-3
0	-1	-2	-2	-2	-2	-2	-2	-2	-2	-3
0	-1	-2	-2	-2	-2	-2	-2	-2	-2	-3
0	-1	-2	-2	-2	-2	-2	-2	-2	-2	-3
0	-1	-2	-2	-2	-2	-2	-2	-2	-2	-3

9.2.9 Monte Carlo simulation excerpt



9.2.10 Detailed results excerpt

Detailed results

Best overall solution	#N/A
Your choice (combined)	WACT
Your choice (separate)	1

Idle time per cycle (s)	LB Line A	LB Line B	LB Line C	Combined (WACT)	Combined (MCT)
Longest Operation Time	912	631	#N/A	136	1218
Most Following Tasks	912	631	77		
Shortest Operation Time	912	631	#N/A		
Least Following Tasks	912	631	#N/A		

# of stations	LB Line A	LB Line B	LB Line C	Combined (WACT)	Combined (MCT)
Longest Operation Time	3	4	#N/A	7	50
Most Following Tasks	3	4	1		
Shortest Operation Time	3	4	#N/A		
Least Following Tasks	3	4	#N/A		

Line efficiency (%)	LB Line A	LB Line B	LB Line C	Combined (WACT)	Combined (MCT)
Longest Operation Time	65%	72%	#N/A	69%	61%
Most Following Tasks	65%	72%	0%		
Shortest Operation Time	65%	72%	#N/A		
Least Following Tasks	65%	72%	#N/A		

Balance losses (%)	LB Line A	LB Line B	LB Line C	Combined (WACT)	Combined (MCT)
Longest Operation Time	35%	28%	#REF!	31%	39%
Most Following Tasks	35%	28%	#REF!		
Shortest Operation Time	35%	28%	#REF!		
Least Following Tasks	35%	28%	#REF!		

Cycle time (s)	LB Line A	LB Line B	LB Line C	Combined (WACT)	Combined (MCT)
Longest Operation Time	879	560	77	63	63
Most Following Tasks	879	560	77		
Shortest Operation Time	879	560	77		
Least Following Tasks	879	560	77		

Throughput time (s)	LB Line A	LB Line B	LB Line C	Combined (WACT)	Combined (MCT)
Longest Operation Time	1726	1608	0	304	1923
Most Following Tasks	1726	1608	0		
Shortest Operation Time	1726	1608	0		
Least Following Tasks	1726	1608	0		

Line balancing KPIs

Idle time per cycle (hrs)	
Separate	Combined
0,31	0,31

# of stations	
Separate	Combined
7	7

Line efficiency (%)	
Separate	Combined
68,6%	69,1%

Balance losses (%)	
Separate	Combined
31,4%	30,9%

KPI clarification:
Idle time per cycle (s): **The times that stations are not actually working**
# of stations: **The integer number of stations**
Theoretical min # of stations: **The minimum number of staions that required to produce the demand**
Cycle time (s): **The time between one product to exit the system and the next products to exit the system**
Throughput time (s): **The time required to produce one product**

9.2.11 Station allocation display

Station allocation Separate

Product A	
Selected rule	1
Priority rule name	Longest Operation Time

Station	Task
1	A
1	B
1	C
2	D
2	E
2	F
2	G
3	H
3	#N/A
3	#N/A
3	#N/A
3	#N/A
3	#N/A
3	#N/A
3	#N/A
3	#N/A
3	#N/A
3	#N/A
3	#N/A
3	#N/A
3	#N/A
3	#N/A
3	#N/A
3	#N/A
3	#N/A
3	#N/A
3	#N/A
3	#N/A
3	#N/A

Station allocation Separate

Product B	
Selected rule	1
Priority rule name	Longest Operation Time

Station	Task
1	A
1	B
2	C
2	D
3	E
3	F
3	G
4	H
4	#N/A
4	#N/A
4	#N/A
4	#N/A
4	#N/A
4	#N/A
4	#N/A
4	#N/A
4	#N/A
4	#N/A
4	#N/A
4	#N/A
4	#N/A
4	#N/A
4	#N/A
4	#N/A
4	#N/A
4	#N/A
4	#N/A
4	#N/A
4	#N/A

Station allocation Separate

Product C	
Selected rule	1
Priority rule name	Longest Operation Time

Station	Task
1	#N/A
#N/A	#N/A
#N/A	#N/A
#N/A	#N/A
#N/A	#N/A
#N/A	#N/A
#N/A	#N/A
#N/A	#N/A
#N/A	#N/A
#N/A	#N/A
#N/A	#N/A
#N/A	#N/A
#N/A	#N/A
#N/A	#N/A
#N/A	#N/A
#N/A	#N/A
#N/A	#N/A
#N/A	#N/A
#N/A	#N/A
#N/A	#N/A
#N/A	#N/A
#N/A	#N/A
#N/A	#N/A
#N/A	#N/A
#N/A	#N/A
#N/A	#N/A
#N/A	#N/A
#N/A	#N/A
#N/A	#N/A

Station allocation Combined

Product ABC	
Selected rule	WACT
Priority rule name	N/A

Station	Task
1	A
2	B
3	C
4	D
5	E
5	F
6	G
7	H
7	N/A
7	N/A
7	N/A
7	N/A
7	N/A
7	N/A
7	N/A
7	N/A
7	N/A
7	N/A
7	N/A
7	N/A
7	N/A
7	N/A
7	N/A
7	N/A
7	N/A
7	N/A
7	N/A
7	N/A
7	N/A

Station allocation Combined

Product ABC	
Selected rule	MCT
Priority rule name	N/A

Station	Task
1	N/A
2	N/A
3	N/A
4	N/A
5	N/A
6	N/A
7	N/A
8	N/A
9	N/A
10	N/A
11	N/A
12	N/A
13	N/A
14	N/A
15	N/A
16	N/A
17	N/A
18	N/A
19	N/A
20	N/A
21	N/A
22	N/A
23	N/A
24	N/A
25	N/A
26	N/A
27	N/A
28	N/A
29	N/A

9.2.12 Final results excerpt

Results
Final sheet

In this final sheet the costs for the two alternatives will be presented. This sheet is presenting the overarching results and primarily intended for the eyes of executives and decision makers.

The summary of investment costs (cells D24 & F24) are based on the average simulation results. The investment costs headings (i.e. area costs, energy consumption and employees) are based on the first simulation as conducted in the sheet "MC", and is not connected to the other calculations in this sheet. Hence, these are mainly used for visual appereance.

Idle time cost (per year) has been calculated through the following formula:
Available production hour per worker * # of shifts * Idle time per cycle (hrs) * # of stations * operator salary per hour

Production costs and investment costs are calculated per lot and per year.

	Alt 1 Separate	Alt 2 Combined
Line balancing KPIs		
# of stations	6	5
Idle time per cycle (hrs)	0,37	0,19
Line efficiency (average)	63%	81%
Balance losses (average)	37%	19%
Production costs		
Balance loss cost (per year)	2 192 008 kr	946 434 kr
Sum	**2 192 008 kr**	**946 434 kr**
Fixed investments costs		
Investment costs	587 694 kr	62 000 kr
Intangible costs		
Area costs	133 606 kr	31 205 kr
Energy consumption	19 102 kr	19 826 kr
Employees	569 415 kr	929 756 kr
Sum	**1 339 436 kr**	**1 013 735 kr**
Grand total:	**3 531 443 kr**	**1 960 169 kr**