JÖNKÖPING UNIVERSITY
School of Engineering

Conceptual Decision Support Tool for RMS-Investments

A Three-Pronged Approach to Investments with Focus on Performance Metrics for Reconfigurability

PAPER WITHIN *Production Systems*

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Abstract

Today's society is characterized by a high degree of change where the manufacturing systems are affected by both internal and external factors. To adapt to current manufacturing requirements in the form of short lead-time, more variants, low and fluctuating volumes, in a cost-efficient manner, new approaches are needed. As the global market and its uncertainties for products and its lifecycles change, a concept called 'reconfigurable manufacturing system' has been developed. The idea is to design a manufacturing system for rapid structural change in both hardware and software to be responsive to capacity and functionality. A company's development towards the concept is often based on a strategy of incremental investments. In this situation, the challenges are to prioritize the right project and maximize the performance as well as the financial efficiency of a multi-approach problem.

The report is based on three different issues. Partly how to standardize relevant performance-based metrics to measure current conditions, how new performance-based metrics can be developed in collaboration with reconfigurability characteristics and set a direction for how decision models can be used to optimize step-based investments. The study is structured as an explorative study with qualitative methods such as semi-structured interviews and document study to get in-depth knowledge. Related literature addresses concepts in search areas such as reconfigurable manufacturing system, key performance indicators, investment decisions and manufacturing readiness levels.

The findings are extracted from interviews and document studies that generate a focal company setting within the automotive industry which acts as the foundation for further analysis and decisions throughout the thesis. The analysis results in sixteen performance measurements where new measures been created for product flexibility, production volume flexibility, material handling flexibility, reconfiguration quality and diagnosability using reconfigurability characteristics. A conceptual decision support model is introduced with an underlying seven-step investment process, analyzing lifecycle cost, risk triggered events in relation to cost and performance measurements.

The discussion chapter describe how different approaches are used during the project that has been revised by internal and external factors. Improvement possibilities regarding method choice and the aspects of credibility, transferability, dependability, and conformability are discussed. Furthermore, the authors argue about the analysis process and how the result has been affected by circumstances and choices. The study concludes that a three-pronged approach is needed to validate the investment decision in terms of system performance changes, cost, and uncertainty. The report also helps to understand which performance-based metrics are relevant for evaluating manufacturing systems based on operational goals and manufacturing requirements.

Keywords

Reconfigurable Manufacturing System, Decision Support Tool, Investment, Key Performance Indicators, Investment Model.

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1 Introduction

This chapter intended to introduce the origins, purpose, and research questions behind this report by describing the challenges that arise in the manufacturing industry and how global competition forces companies to invest in projects that lead to both performance and profitability. The later part of the chapter contains delimitations and outlines for the thesis.

1.1 Background

The pace of societal change is often described to be at an immense level, and the perception that this development will continue makes the ability of adaptation crucial (Rippela, et al., 2016). Manufacturing systems are always affected by external factors (customer-driven) and internal (company-related) (Van Mieghem, 1998). External changes could, for example, be products, technology, customer demand, and demands for customization. Internal factors include business strategy and volume-related challenges (Koren, 2010). With the increased amount of uncertainty, the acquisition of appropriate production equipment is difficult for upcoming product generations (Rippela, et al., 2016).

Capital budgeting involves a long-term decision-making process that determines the best investment in capital goods, such as plant, production equipment, but also other projects worth pursuing in terms of expected benefits (Fechter, et al., 2019; Rashidi-Bajgan, et al., 2010). The main purpose of investments includes generating future cash flows for the organizations (Rashidi-Bajgan, et al., 2010), and capital budgeting historically prioritizes projects based on the maximizing economic utility to the firm (Nelson, 1986). However, competitive markets require multiple objective considerations while doing so (Kahraman & Tolga, 1998). Minimizing the capital cost of equipment, maximizing productivity, minimizing performance disturbance, ensuring high quality, predicting future trends, and rapidly addressing market shifts are all objectives that need to be considered while investigating different options (Kahraman & Tolga, 1998). The extensive use of, and free interpretations of words like productivity and performance have led to misunderstandings. These words have thus become ambiguous terms, which need clarification (Tangen, 2002). Tangen (2002) has developed a model, which explains the relationship between performance, profitability and productivity, input, output, effectiveness and efficiency. *Productivity* is the result of all products produced with the required quality (output) divided by all the resources consumed within the transformation process (input). *Profitability* is the quotient of input and output but is influenced by price-factors (price-recovery). As an umbrella term, *performance* aims to involve non-cost factors, such as speed, quality, delivery, and flexibility into manufacturing excellence. *Effectiveness* addresses the factors that are involved with the output of the transformation process, where *efficiency* is related to the utility of the input resources. The model is illustrated in Figure 1.

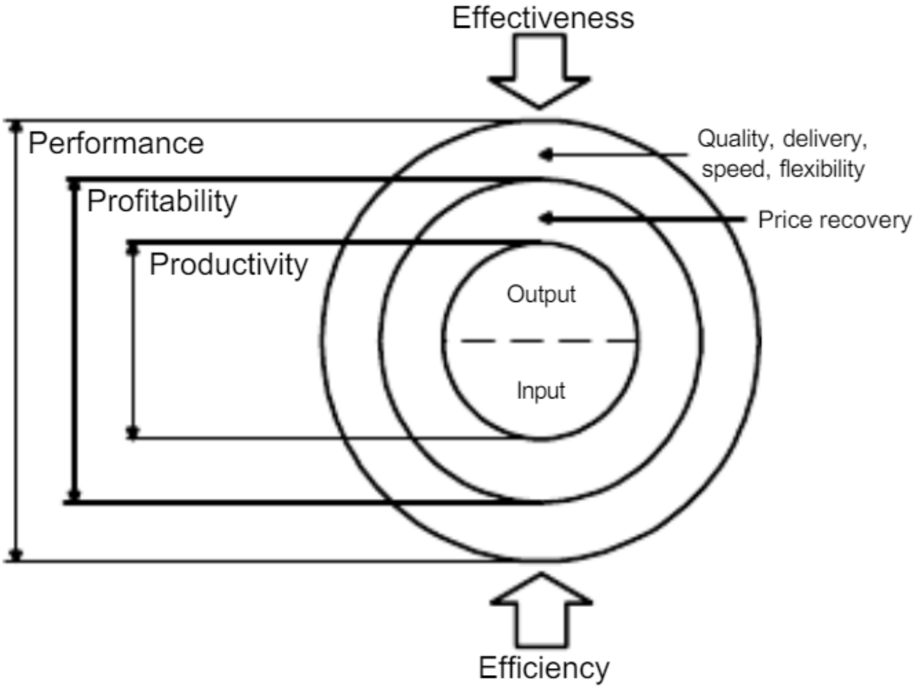

Figure 1 - Tangen's (2002) Triple P Model

A company's profitability strategies have historically been based on economies of scope or economics of scale, which have affected the manufacturing systems to be developed to focus on either capacity or functionality (Koren & Shpitalni, 2010). A dedicated manufacturing system (DMS) is built to manufacture an individual product with high capacity (Mehrabi, et al., 2000). The upside of this concept involves the potential of reaching extensive throughput cost-effectively with the high utilization of tools and machines (ElMaraghy, 2006). However, this comes at the expense of the ability to produce a variety of products since most product changes require modifications of the manufacturing system, which, as a result, adds extra investment costs and rebuilding time (Koren, 2010). Flexible Manufacturing System handles a high level of flexibility and functionality but is restricted to its capacity. In reality, this means that the system can produce a variety of products on the same line, but the rate of production is low, and the cost of equipment acquisition is much higher (ElMaraghy, 2006).

Reconfigurable manufacturing systems (RMS) was developed to cope with foregoing challenges and to stay competitive by cost-effectively responding to quick market changes in product variety and capacity (Koren, 2014). Companies do often have components or machines that are aligned with the philosophy of RMS, but to fully utilize the concept, firms have to adopt new policies and change their mindset in order to gain system benefits (Koren, et al., 1999). However, every organization needs to adopt the appropriate manufacturing setup for their specific conditions. An assessment model should be used to ensure whether the concept is applicable for their circumstances and how to invest in these capabilities towards a sustainable future in economic and environmental terms (Bergström & Jödicke, 2019). Bergström and Jödicke (2019) have developed an assessment model to ease this problem by mapping and evaluating the system effects of different system characteristic enablers. The usage of assessment models helps organizations to understand the current system capabilities and constraints, which creates possibilities of setting improvement targets to be more responsive to internal and external changes. Even if the company decides to choose another manufacturing system, the firm can still have an open mindset and decide upon which reconfigurable level to have in a certain line or machine (Andersen, et al., 2018).

1.2 Problem Description

Electrical engines are currently acting as a disruptive innovation within the automotive industry. This forces companies to switch partly or extensively from internal combustion engines to plug-in hybrids and battery electrified engines (Hertzke, et al., 2018; Wu, et al., 2019; IEA, 2019). New product parts and technologies create significant disruptions and fundamentally change the way engines have been manufactured over the last century. This development creates a higher level of uncertainty for the production department to plan for future processes, machines, and equipment needs (Wu, et al., 2019). Industry consultants perceive that the demand of product mixes and production volumes are difficult to estimate in the upcoming ten years, but it is the expected lifetime of many machines and equipment that needs to be purchased today (Hertzke, et al., 2018; Wu, et al., 2019; IEA, 2019). To cope with the higher level of risks, an increased amount of flexibility is needed since it acts as a "counterbalance" to uncertainty (Newman, et al., 1993). Kampker, et al. (2013) claims that there are three main kinds of flexibility that need to be addressed in a manufacturing system. *Product flexibility* describes the ability to produce a changing set of products without significant changes to the system as replacement and development of resources. *Mix flexibility* explains the system's ability to produce a variety of products in the same system. The third mentioned type is *volume flexibility*, which explains the system's ability to vary the volume of the products without a significant change in production costs (Kampker, et al., 2013).

One problem connected to the extensive focus on non-flexible equipment includes when product lifespans decrease to the point where manufacturing equipment cannot get the return on investment, in other words, some types of machinery will be outdated by its technical maturity lifetime before the economic lifetime**.** This implies that large machine purchases need to be depreciated in a shorter period, or accounting gets a lump sum for the remaining depreciation when the machine becomes obsolete. This will occur in organizations where investment cycles are closely related to product cycles and, thus, create a short-term purchasing strategy. More uncertainty is created if the manufacturing department cannot expect the equipment to be used in new generations of product families or different platforms since it might require a different technology.

Implementing reconfigurable manufacturing system concepts generate value to the firm by its utilization of capacity with high levels of flexibility (Andersen, et al., 2018). Nevertheless, RMSs tends to have a higher purchasing cost than specially designed equipment for a sole purpose. Therefore, it is challenging to motivate a cost to handle the uncertainty of product, mix, and volume. The transition from an existing manufacturing system towards reconfigurability needs investments. It could differ between purchases of entire systems to individual workstations and tools. Usually it is not possible to purchase a new line to apply the philosophy, instead incremental investments are applied. Nevertheless, the investment procedures and techniques have not changed, which makes it difficult to value the monetary benefits of flexibility in a normal discounted cash flow technique (Rippela, et al., 2016). The current state needs to be addressed to know if the investment leads to system improvement. One method of evaluating system performance involves key performance indicators that are aligned to the firm's overall strategy and goals. The literature has investigated the economic feasibility of reconfigurable manufacturing systems concepts in general terms. On the other hand, no one has created a decision support tool that motivates and justifies stepwise investment decisions on equipment and machine levels with associated system performance changes generally and reconfigurability, in particular.

Scenarios with high numbers of data and multiple-objective approaches create challenges for decision-makers to make a rational decision considering the difficulties in analyzing and collating all relevant data. The decision support tools can function in this environment, and the academy has proven to be an adequate method for dealing with this kind of problem as it collects information and suggests the optimal solution based on programmed prerequisites (Kalbar, et al., 2016). Since the concept is presented, defined and developed in the academia: information, sociolects and knowledge barriers arise to the industries. Is there a way to integrate well-known industry terms for defining performance? According to Tangens (2002) definitions, the paper aims to combine overall performance with profitability and productivity measurements within a model. This focus can enlighten the financial benefits of implementing the reconfigurable manufacturing system and create transparency to see how investments can refine the process. In summary, the developed model is intended to be used to invest in the right types of enablers to maximize its intended system performance for a minimal cost.

1.3 Purpose and Research Questions

The purpose of the study is to set a direction for further research of decision support tools that supposed to maximize the expected economic utility of stepwise investment towards a reconfigurable manufacturing system setting. By doing so, the first research questions address the current reconfigurable manufacturing system performance with key performance indicators:

- RQ 1 - How can standardized key performance indicators be used to display the current and expected performance of a reconfigurable manufacturing system?
- RQ 2 – How can reconfigurable system characteristics support the development of new key performance indicators where the academia lacks bearing?

The knowledge of system performance is supposed to be used to evaluate investment alternatives and their effect on performance and reconfigurability measurements. The operational terms can now be set in comparison with financial parameters and risks to feed data into decision support tools that can help firms to optimize economical utility.

- RQ 3 – How can a conceptual decision support tool be structured to facilitate stepwise investment decisions with associated key performance indicators?

1.4 Delimitations

The paper will exclude articles from the scientific field of key performance indicators that do not interact and/or comply with the reconfigurability concept. The investment field is tilted towards understanding which methods are used for valuation in uncertainty since it is the counterbalance to flexibility and, therefore, excludes scientific research. The idea is not to develop a solid mathematical model but a direction for which aspects should be considered when developing and programming a decision model. The following list will mention the more detailed delimitations that the report assumes.

- The report will not cover uncertainty in a macro-financial perspective.
- There are many kinds of key performance indicators, and this report will not cover KPIs that do not involve the internal processor/and economic factors.
- The tool will be developed for an existing factory with an associated machine fleet that wants to calculate replacement equipment investments and will hence not prepare for new manufacturing system creation.
- The analysis will be conducted for the factory and system-level but will be prepared for the implementation of the workstation level.
- The report will not cover any analysis of the organizational structures but is mentioned for understanding.
- The report aims to study the relationship between system performance of different machines with monetary values and, thus, will mention but not analyze the workers' or environmental interactions with the machines and their effects.

1.5 Outline

The report is divided into eight different chapters, where the first introduces the reader to the topic and gives a background to the problems that arise in relation to the topic. This is followed by defining the purpose, which results in three different research questions. The chapter ends with setting boundaries and describing the outline. The method part, chapter two, is divided into several sections that describe the study approach and how the author has structured the work to achieve credibility. Chapter three builds a theoretical background for the subject by describing reconfigurable manufacturing systems, key performance indicators, investment decisions and manufacturing readiness level. It is followed by chapter four, which gives insights about the focal company circumstances. The subsequently three chapters provides the analysis methods and argumentation to answer each research question separately, chapter five introduces the found key performance indicators and the standardization phase used. Chapter six presents the newly-composed indicators in relation to RMS core characteristics, and the next chapter helps to create a conceptual decision support tool towards reconfigurability transformation. Finally, a discussion and conclusion are made in chapter six, where recommendations for further research are given. Chapter six consists of references, and appendices can be found in chapter seven.

2 Method and Implementation

In this chapter, it will be explained how the authors has chosen their approach to the studied problem and how they have proceeded the study. Techniques and methods will be presented and motivated throughout the chapter.

2.1 Research Approach

The phenomenon investigated in this thesis is related to how the industry motivates an investment that does not support current investment models. To understand how the industry works with key performance indicators (KPI) and investment models, the first research question (RQ) were constructed. The second RQ aims for an understanding of how academia defines reconfigurability and what key performance indicators can be combined. RQ 3 aims to understand how KPIs can be translated to fit and make a comparable investment model for a reconfigurable manufacturing system (RMS). Compared to a production system (DMS/FMS) or if there are some substantial KPIs that need to be considered for an RMS.

Before the scope was set a pre-study, with initial unstructured interviews were carried out with a project manager from the focal company. This, along with several meetings with the school of engineering created a scope that should be aimed for. After the scope had been approved by all participants an initial literature search in the field was conducted to see what relevant theories that existed in the area. It also helped prepare for the latter literature search.

The conducted study aimed for an inductive approach with a theory generating reasoning (Williamson, 2002). The strength of the approach is the open mindset as it helps the researchers to maintain and not disclose any alternatives. Although, constant reinterpretation can lead to new important findings that need to be taken into consideration (Williamson, 2002). Since the maturity level of the chosen research area was low, the need for an explorative method (Booth, et al., 2016; Paul, et al., 2019), with clear context and rich data collection was needed. Therefore, a qualitative study was chosen. When conducting a qualitative study, the aim should not be to find a problem through the literature review instead the problem should be understood through interviews and other methods (Yin, 2016). This is supported by the approach as the problem has been identified through interviews.

A qualitative study by Booth et al., (2016) has a strength in being explorative, which supports the purpose of this study. Although it has weaknesses such as being time-consuming and complex to carry out when gathering primary data (Paul, et al., 2019). The primary data was collected through interviews as a single case study in parallel with the literature review while the secondary data was gathered through a literature review and document study. A questionnaire was used to confirm the information by the rest of the department. Through gathering information from different methods, methods triangulation could be obtained which helped to strengthen the trustworthiness of the study and will be further described in 2.5 (Yin, 2016; Williamson, 2002).

To answer the research questions, the authors started with unstructured interviews followed by a literature review that should form the base of our knowledge within the research area. The following methods were used to answer the research questions and can be seen in Figure 2.

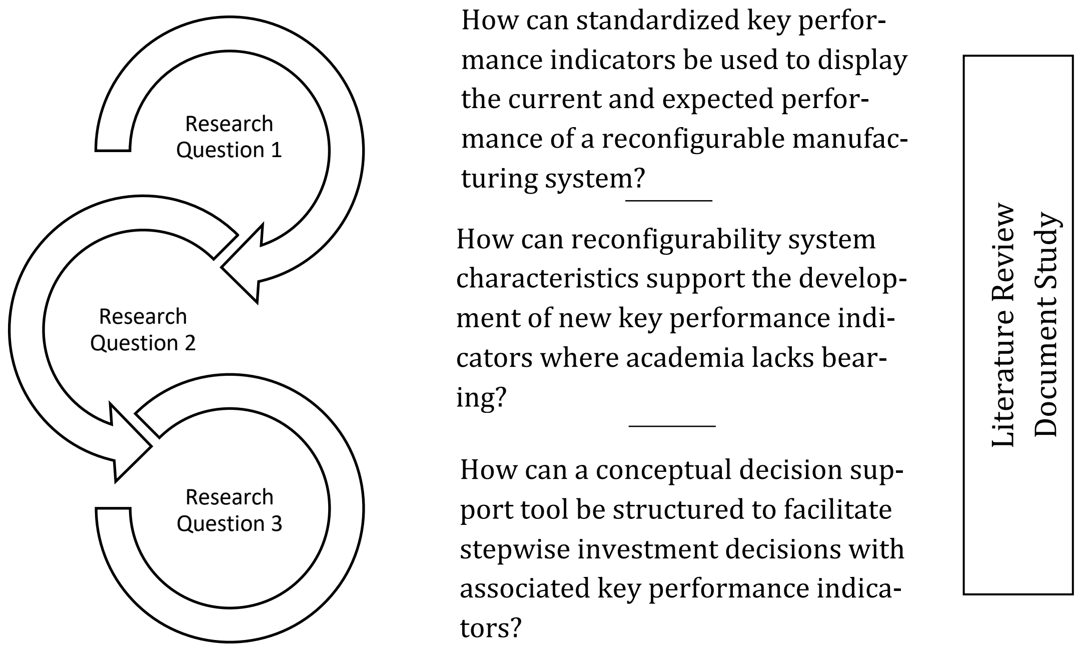

Figure 2 - Research Questions Process and Methods

2.2 Literature Review

Through the literature review, the main goal was to identify, locate and analyze the current field of the chosen areas (Yin, 2016; Williamson, 2002). As the literature review brings a deeper understanding according to Marshall & Rossman (1995) as well as the correct context for it, it needs to be carried out in a systematic way to ensure all data has been collected. Through working in a systematic approach with techniques as Boolean and Phrase search in the different areas an efficient and explorative approach was carried out as described by Booth, et al., (2016). To ensure that the literature was conducted in a systematic approach it was important to register and motivate every step that was taken. The following model described by Tranfield et al., (2003) was followed during the analysis which is very similar to Wolfwinkel et al., (2011) model and has a proposed framework with 3 stages that consist of: Stage 1 - Planning the Review, Stage 2 – Conducting the review and Stage 3 – Reporting and dissemination. During the first stage, initial search was made and a plan for what areas the search should be conducted in was chosen. In the second stage in the Wolfwinkel et al., (2011) model, critical thinking and a process of 'article analyzing' were used to evaluate the articles found. The analysis tool was developed by Booth et al., (2016) and helped to select the most appropriate articles. The process was chosen due to its logic and transparency when selecting articles and can be seen in Figure 3 - Process of Selecting Studies Figure 3. In the third stage all articles were broken down to what they said about the areas they were written about. The model also proposes a methodological order that is easy to follow and has a natural approach to handle the articles. By working in a structured way, it will increase the possibility to replicate the same work process that has been conducted.

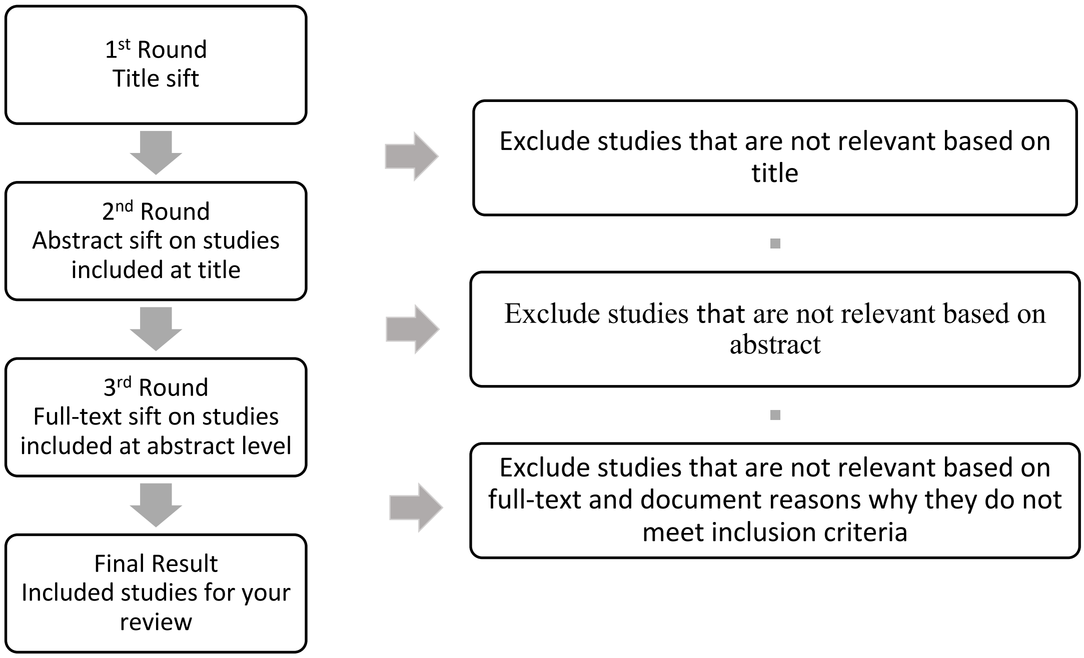

Figure 3 - Process of Selecting Studies (Booth, et al., 2016)

2.2.1 Literature Search

The literature search was based on the pre-study that was conducted at the beginning of the project. Three main areas were located and divided into reconfigurable manufacturing systems, key performance indicators (KPI) in relation to RMS and investment decisions. Through an extensive literature research in these fields, the aim was to answer our three research questions.

The database and search engine Scopus were used that provide peer-reviewed articles from firms and journals that publish scientifically articles. The topics chosen for the search were conducted through a 'boolean' and 'phrase search' technique as described by Booth et al., (2016). Boolean search is a technique where different types of words i.e. AND, OR is used to perform a precise search (Booth, et al., 2016). The phrase search technique was used to search for specific words in the academia. When the search phrase was entered, the functions sorting tab were used to find the most relevant articles. Normally the tab is automatically in sorting mode for "newest to oldest" in sorting. Because the authors chose to do multiple searches that resulted in a variety of hits, sorting by relevance was considered to produce articles with a higher probability of reaching the study's scope than sorting the articles from newest to oldest. The analysis was carried out according to the process in Figure 3 (Booth, et al., 2016). "1st Round" – Title sift, "2nd Round" - Abstract read, "3rd Round" - full text and "final result" – articles included in the theory. Exceptions from the model were that, to make sure all areas where covered from the articles, the literature technique snowballing as described by Yin (2016) was used. Interesting articles were picked and stored in a shared document on google drive to be further evaluated. In total 27 articles were chosen through the snowballing technique. The articles were chosen from the topic in the text and then it followed the process from Booth et al., (2016) seen in Figure 3. The literature acquiring process of the different subjects will be described shortly and the search areas with associated search phrases will be displayed in Table 1.

Reconfigurable Manufacturing System - The thesis aims for a general and broad picture of the field to provide understanding of the concept, the relationships between system aspects within a firm and system characteristics. This resulted in the theoretical framework seen in chapter 3.1. The search words used for reconfigurability can be seen in the following Table 1.

Key Performance Indicators – The literature review for KPIs intends to give deeper understanding for data points (special data picked from the production which is added to an equation to form a KPI) and measurement which are related to reconfigurability characteristics to display manufacturing system capabilities and investment decisions effects of investments. The extract of this process is reported in chapter 3.2. The search words for KPI in relation to RMS can be seen in Table 1.

Investment Decisions – For this part (chapter 3.3), the focus is on understanding how the academy views investment and the capital budgeting process from a general perspective, but also the reasoning about uncertainty and flexibility in procurement as ca n be seen in Table 1.

Manufacturing readiness level – The literature review conducted for manufacturing readiness level was conducted due to the focal company's usage of the model and gave the authors a deeper understanding. The key factors to understand was the process and meaning of the criteria's defined within the model. The search words for MRL can be seen in Table 1.

Table 1 - Outcome of Literature Search Process

Search phrase using Scopus	# of hits	1st round	2nd round	3rd round	Result
Reconfigurability					
((“Reconfigurable Manufacturing Systems” OR Reconfig*) AND (Production Systems OR “Manufacturing Systems”) AND Characteristics)	278	40	14	5	5
Key Performance Indicators					
“Key performance indicators” AND “Reconfigurable manufacturing system”	7	6	3	3	3
(Reconfig* OR RMS) AND (Manufacturing or Production) AND Assessment	381	40	15	9	9
("Key performance indicators" OR reconfig*) AND manufacturing AND assessment AND RMS	25	25	17	13	13
("KPI " OR "Key Performance indicator") AND ("manufacturing" OR "production")	1897	20	6	2	2
Investment Decisions					
“Capital budgeting" AND (manufacturing OR production) AND decision	96	9	6	6	6
"investment decisions" AND (manufacturing OR production)	1867	40	21	6	6
"capital budgeting" AND parameters	94	11	2	2	2
"investment" AND reconfig*	913	14	8	8	8
"Cost calculation" AND reconfig*	11	2	2	2	2
Manufacturing Readiness Level					
(“Manufacturing Readiness Level” OR MRL) AND Manufacturing	81	5	3	2	2

2.3 Case Study

In the following section it will be motivated why interviews, document analysis and questionnaire were chosen as case study methods in this study.

2.3.1 Case Selection

The case chosen to be studied was the investment process of acquiring new machineries at the focal company. Paul et al., (2019) and Williamson (2002) describes a case study as when developing an understanding of a social phenomenon in their natural setting which is unknown or poorly understood. The problem that was analyzed required a single-source case study where the problem was analyzed in-depth rather than widely. The methods should also give the authors the possibility to gather data without an extensive knowledge in the area. Therefore, interviews and document analysis were chosen as main data gathering techniques. Although data collection techniques can be both from a quantitative- or qualitative approach as described by Paul et al., (2019). So, as a compliment, a questionnaire was chosen which can be a method of verifying the interviews with one or several departments that share the same knowledge as the interviewees.

Though researchers are arguing that case study design is too influenced by the level of the researcher and that the subjectively gets limited if the level of the researcher is too low (Yin, 2012; Williamson, 2002). If so, this could decrease the trustworthiness of the research (Yin, 2012). To decrease the influence from the authors an unstructured interview design was chosen which are further explained in chapter 2.3. As Yin (2012) defines unstructured interviews can be good to use when the interviewer's knowledge within an area is low. Through conducting unstructured interviews, the interviewee gets the possibility to cover the area with the knowledge the person has.

2.3.2 Data Collection

Through the qualitative approach, data collection methods for this study has been gathered from techniques as interviews, document study and questionnaire. They are common techniques used within qualitative studies (Paul, et al., 2019).

Interviews

The initial interviews that were carried out at the beginning of the project were of unstructured characteristics. The authors had little knowledge about the topic and needed to explore the area and see what data that could be collected. The interactions contained one or multiple people with the aim to gather data (Yin, 2016) and to gain knowledge about the specific topic with people from both the focal company and academia. The reason interviews were conducted with both people from the academia and the industry was to get an in-depth view on the complex problem (Leedy, et al., 2019; Williamson, 2002).

To be able to gather as much relevant data as possible, the most suitable interviewees was chosen together with the focal company. The unstructured interviews aimed to gather data on how they work with investment decisions and what key performance indicators are used in decision making. The interviews were conducted through eye to eye meetings or through skype where several of the interviews were audio recorded. Both authors were present at the interviews and a record with the persons involved can be seen in Table 2.

Table 2 – Interviews

Interview type	Involved	Topic	Length (min)	Date
Unstructured	Production engineer 1, Supervisor.	Project Description and initial thoughts, RMS	60	20200122
Unstructured	Production engineer 2, Global director.	Project Description, initial thoughts, and RMS	60	20200225
Unstructured	Production engineer 1.	Updates from focal company project and RMS	30	Weekly 20200213-20200318
Semi-structured	Controller.	Investment process	60	20200317

Document Study

Document studies were carried out to deepen the knowledge within the research subject and their internal processes in the focal company. Yin (2016) describes the strength in document studies and how it can help with the right context. Yin (2016) also raises the concern that the researchers need to be careful collecting the data as it cannot be known if the data has been refined. Although Skärvad & Lundal (2016) describe it as a good complement to other data collections methods.

The documents that were received contained information about their KPI and were used to complement the literature review and understand how the focal company works with the information extracted from the production. It also gave a deeper insight into what KPIs and facts the top management look at when deciding in investments. The authors also received documents regarding their internal processes for projects and how different maturities on both products and production equipment were calculated. The knowledge helped to construct questions for the interviews and create a better understanding of the problem faced. The documents received can be seen in Table 3.

Table 3 - Documents Received

Date	Description	Source
20200227	Synchronized Investments	Production Engineer 1
20200227	Resource Allocation	Production Engineer 1
20200227	Product Realization Process	Production Engineer 1
20200131	Value stream mapping	Production Engineer 1

Data Analysis

The data gathered through interviews were compared to the literature review and document study to see similarities and try to find common KPIs and processes. This to find a framework that could found the base for the investment decision. The questionnaire was analyzed and compared to the model to see if all aspects were gathered. The three methods contribute to the triangulation of the data collection methods which increases the validity (Paul, et al., 2019; Williamson, 2002; Yin, 2016). The analysis can be compared to Yin (2016) five-phase cycle, which contains the following steps: 1 – Compiling, 2 – Disassembling, 3 – Reassembling, 4 – Interpreting, and 5 – Concluding.

Through the literature study and the interviews at the focal company, it was clear that the reason a company invests in a reconfigurable manufacturing system depends on variables as ‘operational performance’, ‘financial’ and ‘uncertainties’. The data collected through the literature search was compiled into the different variables defined above. The data collected was then disassembled within each variable and further analyzed. For operational performance, it required a more in-depth analysis. The data analyzed was reassembled into subcategories within each element. When the structure was clear, the data points were matched to the ISO- standard to increase the transferability and generalizability. The data points and their belonging KPIs that could not be matched to the ISO – standard was redefined, and new data points were created that could be matched with performance measurements.

When operational performance, financial and uncertainties were defined the decision investment model could be structured. The first step in the model is to present the reasons and give the reader a deeper understanding of RMS and the investment it will present. The second step is to fill up all the data points defined in operational performance and put in how the system should change. Also, constraints should be filled in here, so specific goals can be achieved or taken into consideration. Then current status is mapped along with KPIs defined and the financial and uncertainty parameters taken from the second step. Also, a page with the future state is autogenerated with the information filled in, in step 2. In the future state, several scenarios will be displayed for each configuration that will highlight different possibilities. Current status and future state are then compared and are summarized in a result page where various pivot tables display interesting data.

2.4 Creation of Key Performance Indicators

When creating a new KPI, a lot of information needs to be described so everyone can understand and see the purpose of the KPI. The KPIs were developed in accordance with ISO 22400 (2014) in regards to defined key parameters as: name, description, scope, formula, unit of measure, range, trend, timing, audience and production methodology criteria was followed (Zhu, et al., 2018).

The KPIs were defined from the literature as it created the foundation for what parameters were missing. They were then explained according to the model by Li, Charlotta, Martina and Massimiliano (2018) and key information was displayed. Data points were then matched against the ISO 22400 – standard (2014) to see if it were possible to match the data points.

2.5 Enhancement of the Credibility

To motivate the study's trustworthiness the authors need to obtain a meaningful result that can create reasonable conclusions and that can be defended through facts (Paul, et al., 2019). Conventional methods like internal/external validity and reliability are not appropriate to use when investigating the trustworthiness of qualitative studies accordingly to researches (Paul, et al., 2019; Yin, 2016; Halldorsson & Aastrup, 2003). Instead, they propose an approach called *Trustworthiness* which the authors have chosen to follow as it is designed for qualitative studies. The concept has the following parts: *credibility, transferability, dependability,* and *conformability*. Each concept contains a set of strategies to strengthen the trustworthiness of the study (Halldorsson & Aastrup, 2003).

2.5.1 Credibility

Credibility is the ability to obtain results, draw conclusions and that the interpretation of gathered data finds credible by other researchers (Paul, et al., 2019). Through choosing an approach that fit the study and following the process connected to that approach, important steps towards increased credibility are taken. By building a base with an extensive literature review to support detailed explained data gathered from well-known techniques and appropriate methods that correlate to qualitative studies, conclusions and relations are well supported. It also gives the reader the ability to draw their own assumptions and conclusions from the study and judge the credibility.

2.5.2 Transferability

For qualitative studies, a reoccurring problem is to strengthen their transferability since the problem often is specific and is surrounded by its own context. Williamson (2002) explains the problem as, subjectively can vary depending on how well, the researchers can carry out various techniques and the uniqueness of every case. However, keeping the transparency through all data gathering techniques will increase the transferability. As when creating the literature-base that has support and backed up statements from the case studies as well as method triangulation important factors of transferability can be strengthened (Paul, et al., 2019; Yin, 2016).

2.5.3 Dependability

Through the method chapter of this study, the process was described, and the authors have tried to be as transparent as possible. Every decision has been carefully explained and motivated. (Halldorsson & Aastrup, 2003)

2.5.4 Conformability

To achieve a high degree of conformability it is important to show that no opinion has been reflected in the result from the authors (Halldorsson & Aastrup, 2003). In the study, several actions have been taken to decrease the level of biases, for example: each area in the literature study is described through multiple sources, data is analyzed through models chosen from a qualitative perspective and carefully explained in this chapter.

3 Theoretical Background

The theoretical background starts with defining reconfigurable manufacturing system (RMS) and motivate the authors choice of characteristics. The chapter 'Key Performance Indicators in Relation to Characteristics' presents the existing literature on Key performance indicators that has been created in different characteristics. The investment decisions chapter has been categorized into three different parts, one chapter aims to present the various ways of analyzing investments on a general basis, others will handle and map the current financial investment evaluation methods, non-financial methods, and methods of investigating and handling uncertainties.

3.1 Reconfigurable Manufacturing Systems

Customer trends involve more product alternatives, customization and personalization with increased frequency of new product generations and associated launches (Koren, 2006). These challenges need to be addressed within both product and production development. The current method of handling these trends within product development has been connected to the usage of modular product architectures, product platforms and product families. However, a similar method has not been historically applied to handle the complexity within production before the implementation of reconfigurable manufacturing systems (RMS). While developing manufacturing systems, consideration should be given to the type of uncertainty that needs to be addressed in the organization (Mehrabi, et al., 2000). Reconfigurability has a way of addressing these challenges by being more responsive, which contributes to the method being more suitable than traditional perspectives (Koren, 2006). The concept of RMS was proposed in the 1990s and is designed around parts families and consists of mixes of flexible, dedicated machines and reconfigurable tools to facilitate a changeable system of functionality and capacity in a cost-effective manner. The relationship between capacity and functionality is displayed in Figure 1Figure 4, where dedicated (DMS), flexible (FMS) and reconfigurable manufacturing systems have been mapped. Koren (2010), defines the concept as:

> *"Reconfigurable manufacturing systems are designed for rapid change in structure, as well as in hardware and software components, in order to quickly adjust production capacity and functionality within a part family in response to sudden changes."*

It is fundamentally important to design and adjust the structure to the intended parts or product family when working around RMS (Koren & Shpitalni, 2010). Therefore, in order to compete with FMS and DMS, the manufacturing system can only be comparable to the product or parts family that it was designed for (Koren, 2006). However, the system facilitates the favorable circumstances of responsiveness to changes and the capacity to be consistently versatile while keeping the requirements of functionality, capacity and cost (Koren, 2006).

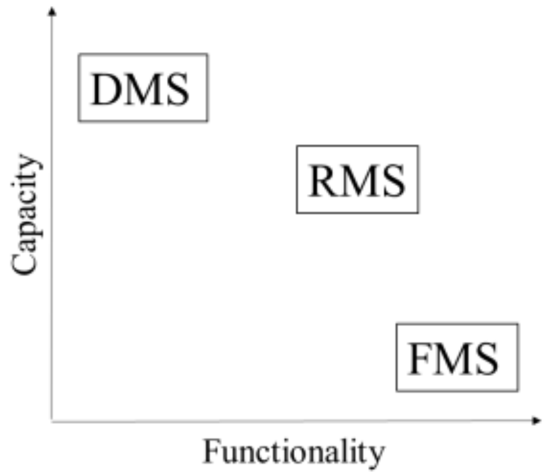

Figure 4 - Capacity and Functionality Mapping of Manufacturing Systems (Koren, 2006)

Reconfigurability can be constructed on different system aspects levels. Wiendahl et al. (2007) have eased the communication of an organization's hierarchical structure by mapping the technical and human resources into six levels. The highest level involves all sites in the organization and is called *network-level*. Individual site level involves buildings and its infrastructure, thus named *factory-level*. The third level *segment* implies all processes needed for a ship-ready product, where *system-level* instead addresses all processes used for manufacturing variants of a product. *Cell-level* means a group of workstations and material handling that refines the product, where *workstations* are defined as the lowest level, which includes machinery and tools that add value to the product. Higher levels are usually affected by strategic goals, visions and policies, and these decisions affect all underlying structures, but small changes in workstations, however, might not generate any major impact on the higher levels (Andersen, et al., 2015). In summary, all these levels are interdependent of each other; therefore, it is important to know that changes more or less affect the other levels (Wiendahl, et al., 2007). The following Figure 5 by ElMaraghy & Wiendahl (2009) illustrates the different system aspects with associated reconfigurability lingo and product structure.

Figure 5 - The System Aspect, Reconfigurability-Lingo and Product Structure (ElMaraghy & Wiendahl, 2009)

3.1.1 Key Performance Indicators in the Different Levels

Connecting to the levels in Figure 5, each level has its own set of KPIs which is translated to the responsibility each manager has. Björkman (2019) maps and conclude that a clear definition needs to be constructed within the organization and communicated in an efficient way for each KPI. Otherwise its usefulness can be perceived differently though the organization. Bhatti, Awan and Razaq., (2014) expresses the importance of having a clear definition of the KPIs, as it is the only way for the organization to check if they are going in the right direction. It also gives them the opportunity to evaluate and control the overall business. Although Raza, Muhammad and Majid., (2016) argues that KPIs are not always easy to measure and to know which should be measured could also bring some challenges.

3.1.2 Understanding Driving Forces and Strategies

Bi, Lang, Shen and Wang (2008) concluded that in order to measure the performance an RMS the contribution to the manufacturing system needs to be assessed through what an RMS wants to achieve. Bi, Lang, Shen and Wang (2008) have mapped the underlying customer demand incentives and converted these into four manufacturing requirements with associated strategies. These are being shown in Table 4.

Table 4 - Manufacturing Requirements (Bi, et al., 2008)

Manufacturing requirements	**Strategies**
Short lead time	Elimination
	Capability
	Structure
	Ramp-up
More variants	Modularization
	Capability
	Reconfigurability
Low and fluctuating volumes	Modularization
	Manufacturing
	Assembly
Low price	Cost
	Productivity
	Rewards

3.1.3 Reconfigurable Manufacturing Systems Characteristics

When designing a reconfigurable manufacturing system, it needs to be from a perspective where hardware and software are prioritized (Koren, 2006). This so the integration of new modules can be carried out quickly and reliable (Koren, 2006). If so, the system will have the ability to be flexible, not just within a product family but with several product families (Andersen, et al., 2018). Koren (2006) has made an in-depth review of what is it that influences the RMS and suggests that RMS contains six characteristics:

scalability, modularity, diagnosability, integrability, convertibility and customization. These are the most common core characteristics mentioned by Napoleone, et al. (2018a) in the literature and has therefore been chosen for this study.

Scalability

Scalability can be defined as the ability to change capacity up and down rapidly and economic sustainability (Napoleone, et al., 2018a). A good way of working with sustainability is defined by ElMaraghy (2006) and is through working with the number of shifts/workers and line balancing.

Modularity

Modularity has been defined by Koren et al., (1999); Napoleone et al., (2018a) as machine modules that can be quickly changed between different manufacturing modules. To achieve a high level of modularity with little cost and effort, a standardized interface that works for all the machines needs to be defined/constructed (Koren, et al., 1999; Mehrabi, et al., 2000; Napoleone, et al., 2018b).

Diagnosability

Diagnosability can be defined as the ability of how quickly a large system can identify either a quality or reliability error (Mehrabi, et al., 2000). Koren et al., (1999) talks about the importance of ramp-up time as the diagnosability needs to be able to detect faulty parts to quickly reduce waste and ramp-up time. Napoleone et al., (2018a) also describe diagnosability as the ability to correct the fault quickly in an operational context.

Integrability

Integrability can be defined as the components ability to be removed or integrated into the manufacturing system with the least impact as possible (Koren, et al., 1999; Mehrabi, et al., 2000). The character of the integrability could be both hardware and software as both programs and machines can change over time (Napoleone, et al., 2018a).

Convertibility

Convertibility is related to the ability to change from one batch to another (Koren, et al., 1999). This can be related to change of equipment, tool and can sometimes even require a manual change. Mehrabi (2000) defines convertibility as the ability to make a quick changeover from existing products and to quickly adapt the system for future products.

Customization

Through designing the systems hardware and software a.k.a capability and flexibility with the product family it can achieve customization (Mehrabi, et al., 2000). Koren et al., (1999) describes it as well with two aspects:

- Customized flexibility - the flexibility that is built into the machines to handle the product family

- Customized control – that is the open architecture that can allow the machines to be controlled so the exact function can be chosen.

3.2 Key Performance Indicators

Key performance indicator is a way of measuring the performance of the work carried out in a company. It can be the top management explaining a KPI to a middle manager and his department so they can set their own goal in order to reach the overarching goal. Often, companies tend to come up or chose which KPIs are the most important for just their company. Sometimes they adjust already existing KPIs, although the most important thing, is that the KPIs chosen are well communicated to the lower parts of the organization.

3.2.1 Existing Key Performance Indicator Structures in Reconfigurable Manufacturing Systems

The academia has different ways of addressing and calculate various characteristics in RMS. Although academia lacks research in models that contain all elements of the RMS system (Khanna & Kumar, 2019), articles that have structured one or multiple characteristics to create a framework for investments can be seen but they do not conclude the holistic picture. A good example that contains the overall view is presented by Mittal and Jain (2014) where they give an introduction to RMS and its core characteristics as they define as modularity, scalability, convertibility and diagnosability. They then proceed to explain how KPIs can be defined within each characteristic. They then connect each KPI with their characteristic and the influence each characteristic has on each other. Furthermore, Khanna and Kumar (2019) are mapping the field of RMS and have done an extensive literature review. They draw conclusions about which areas that had the biggest impact depending on the number of articles published about the area but also where future research needs to be attended. The lack of research lay within diagnosability, integrability and convertibility. It also shows that the most common way of putting all the information together is from soft computing (Khanna & Kumar, 2019).

Within the characteristics there exist theories that try to explain how you can improve various settings. Lee (1997) talks about the possibility to design a component after certain data points and KPI that will help the product fit in a reconfigurable manufacturing system. Then the design is evaluated in the system through formulating KPI that assesses the system. Goyal, Jain and Jain (2012b) has identified a gap in the literature where the interactions between the modules on a machine level have not been thoroughly investigated. Since integration is an important characteristic for making reconfigurability efficient Goyal et al., (2012b) proposes a comprehensive approach to find the best solution. The approach makes a clear trade-off for responsiveness and economy where the first one is to be prioritized to increase the integrability.

Xie, Xue and Zheng (2009) have created a performance evaluation system where they analyze the manufacturing system as a whole through six aspects, economy, capacity & functions, reconfigurability, reliability, environmental friendliness and risk. The aspects are then further categorized to analyze the manufacturing system, the authors have chosen 20 KPIs that have the intention to address the manufacturing system as well as evaluating the RMS

Abdi (2009) Has defined seven criteria's capacity, functionality, operating cost, quality, overhead cost and capital cost that needs to be assessed in order to measure the level of a reconfigurable manufacturing system. The model builds fuzzy numbers and the relation between the KPIs found and creates scenarios so the best solution can be chosen.

Garbie (2014) identifies the need of evaluating an RMS together with performance measurements cost, response, system productivity, people behavior, inventory and quality as the critical objectives for an organization are highly dependent on the manufacturing system. Garbie (2014) states that an RMS can be evaluated in both quantitative and qualitative measurements but to be able to compare it with the performance measurements a qualitative approach was chosen.

Mittal and Jain (2014) define eight performance parameters that need to be accounted for when deciding the most optimal configuration strategy. They further explain how to calculate a configuration of a machine in the most economical way and what parameters are important for that specific part.

Abdi & Labib (2004) discuss the importance of analyzing the manufacturing system before designing an RMS. They propose a model that stresses the importance of capacity and functionality during the reconfiguration phases in an RMS. The model is designed to handle both technical and economical perspectives to give the best feasible study.

Bi, Lang, Shen and Wang (2008) have identified that RMS cannot be evaluated with system performances through its characteristics. Instead, the system needs to be translated to what it needs to achieve. Bi, Lang, Shen and Wang (2008) explain that a manufacturing system's core characteristic is to develop the following manufacturing requirements shown in Table 4. The Requirements will not only enhance the whole manufacturing system but also the elements that affect the RMS.

A list of all KPIs found in the literature can be seen in Table 5

Table 5 - Key Performance Indicators Found in the Literature

Criteria	Objective
Design cost Reconfiguration cost Running cost	*Economy* (Xiaowen, et al., 2009)
System productivity Equipment Utilization Process Capacity limits Balancing	*Capacity and functions* (Xiaowen, et al., 2009)
Equipment reconfigurability Process reconfigurability Logistic reconfigurability	*Reconfigurability* (Xiaowen, et al., 2009)
Ramp-up time Diagnosability Mean time between failures System availability	*Reliability* (Xiaowen, et al., 2009)
Optimal use of resources Security Friendly interface	*Environmental friendliness* (Xiaowen, et al., 2009)
Technology risk Organize risk Market risk	*Risks* (Xiaowen, et al., 2009)
Set-up time Changeover time Varity	*Capacity* (Abdi, 2009)
New product introduction Mobility Volume	*Functionality* (Abdi, 2009)
Labour Maintenance Work in progress	*Operating cost* (Abdi, 2009)
Convenience of use Reliability Accuracy Compatibility	*Quality* (Abdi, 2009)
Price Install Tools and fixtures	*Capital cost* (Abdi, 2009)
Overhead cost	*Overhead cost* (Abdi, 2009)
Efficiency Risk Safety	*Performance* (Abdi, 2009)
Manufacturing cost Overtime cost Additional cost	*Cost* (Garbie, 2014)
Material Handling Flexibility Production Volume (Demand) Flexibility Product (Mix) Flexibility	*Response* (Garbie, 2014)
System utilization Manufacturing lead time Production Rate	*System productivity* (Garbie, 2014)

Criteria (cont.)	*Objective (cont.)*
Hiring	*People behavior* (Garbie, 2014)
Rejection	
Motivation	
Fired	
Work in progress	*Inventory* (Garbie, 2014)
Final product quality	*Quality* (Garbie, 2014)
Cost	*Overall* (Mittal & Jain, 2014)
Reliability	
Utilization	
Quality	
Availability	
Lead time	
Ramp-up time	
Reconfiguration time	
Responsiveness	*Overall* (Abdi & Labib, 2004)
Product cost	
Product quality	
Inventory	
Operator skills	

3.2.2 ISO-Standard 22400

When developing new KPIs or changing already existing KPIs to fit into a new formula or meaning it is important to use some sort of already rooted theory. A good example of rooted theories within the manufacturing industry is standards (2014). Through the following standards, a broader perspective can be taken and the possibility for more companies to use the same model or framework is possible. Through looking at ISO standard 22400 (2014) 37 KPIs could be identified with 51 data points as a basis. These can be seen in Table 6.

Table 6 - ISO Standard 22400

ISO – Standard 22400 KPI headers	Quantity
Planned times	5
Actual times	14
Maintenance times	6
Logistical elements	16
Quality elements	9

3.3 Investment Decisions

There are multiple approaches that need to be addressed in terms of analyzing an investment. A common approach includes cost-calculations. Fechter, et al. (2019) have developed a cost calculation model with a leasing approach of manufacturing equipment were fixed cost is being held by an external, fictive department, and the variable costs with leasing fees act as a basis for determining the feasibility of the investment. The model is motivated by the fact that shorter product lifecycles will lead to the inability to bear their own expenses and initial investment decision (Fechter, et al., 2019). Heilala, et al. (2008) does account for the production system life cycle, changeability, and reconfigurability analysis apart from the provided cost calculations by looking at the total cost of ownership during its lifespan.

Discounted cash flow techniques such as: discounted cash flow (DCF), net present value (NPV) and internal rate of return (IRR), have traditionally been the dominating investment criterion within the field, but these procedures tend to ignore the upside potential of management flexibility (Jiao, et al., 2006). As reconfigurable manufacturing systems (RMS) are developed to handle quick changes and fluctuating market demand, Fecther, et al. (2019) argues that the traditional evaluation methods and tools fail to account for the benefits reconfigurable systems can provide for the firm (Abdi & Labib, 2004).

A sole focus on cost fails to account for improved customer satisfaction, capacity changes, functionality degree, and reconfiguration time and cost (Abdi & Labib, 2004). To handle this, Abdel-Kader (1999) proposes a framework of measuring the expected performance of a reconfigurability-investment in three different aspects. The first aspect handles the financial returns of the investment in a traditional capital budgeting technique, the second approach evaluates the investment form non-financial criteria, and the third perspective involves risk (Abdel-Kader, 1999). Another multi-approach is carried out by Heilala, et al. (2008) that have developed a cost calculation that also considers the production system lifetime and its ability to change and reconfiguration. Furthermore, Abdel-Kader (1999) suggests transforming results from different aspects into fuzzy numbers to merge the analysis and provide a concluding value for investments. Rashidi-Bajgan, et al. (2010) have developed a model with a mathematical programming approach within a fuzzy environment to address the multi-variable capital budgeting problem.

Valuing flexibility is a difficult task accordingly to Kulatilaka (1988), but the benefits of flexibility include changes of indirect and direct cash flows, its ability to handle uncertainty, but also nonpecuniary effects such as learning value. Andersen, et al. (2018) also stresses the importance of considering the uncertainties within the calculations when evaluating and justifying investment decisions of new reconfigurable equipment as it is the main driver of implementing the reconfigurability concept. The downside of the notion is that reconfigurable equipment creates an initial higher procurement cost, which emphasizes the challenge to find and evaluate the breakeven point between more dedicated alternatives (Koren, et al., 2018).

MacStravic & Boucher (1992) have generated software that could be used with capital investment analysis of manufacturing equipment. The program incorporates cost with difficult-to-quantify benefits, and the process divided into five steps seen in the following Table 7.

Table 7 – Software Investment Process (MacStravic & Boucher, 1992)

1. Identifications of investment alternatives and evaluation criteria
2. A subjective judgment of relative importance of criteria
3. Computation if implied annual benefits or cost of criteria and investment alternatives
4. Judgment with respect of carinal transitivity and implied economies of scale is investigated
5. Combine annual benefits of alternatives with investment costs, time horizon, discount rate, and depreciation amount and performs a net present value analysis of the alternatives.

3.3.1 Financial Returns

There are different ways of prioritizing projects in capital budgeting both in academia and companies. The following Table 8, covers all capital budgeting techniques and one accounting concept that has been found during the literature review process.

The most commonly used measure is Net Present Value (NPV), which is applicable for capital replacement projects with minimal risks but is perceived as insufficient to account for uncertainties (Nelson, 1986; Ross, et al., 2013). For this reason, there is criticism of using traditionally capital budgeting techniques as NPV within the manufacturing equipment acquisition field (Fechter, et al., 2019). Instead, it is important to assess the lifetime costs associated with the investment since procurement costs are not an enough measure of investment effectiveness (Heilala, et al., 2008). Fecther, et al. (2019) agrees that lifecycle cost is a "framework that allows assessing costs and benefits over all phases of realization and machinery use" which is beneficial since major benefits arise on system and factory levels (Khanna & Kumar, 2019).

Life Cycle Costs (LCC) is the sum of all estimated costs from initiating projects to the disposal of both equipment and the project. The goal of doing an LCC is to be able to choose the most cost-effective solution during its lifetime. The method can be applied in different ways with different cost parameters and thus there is no limit to what can be included in the calculations if comparable investigations are made on the alternatives being compared. The various cost parameters that can be included are design, development, production, operation, maintenance, disposal, and support. (Kampker, et al., 2013; Heilala, et al., 2008)

3.3.2 Early Equipment Management

Early equipment management (EEM) is an extraction from the lean philosophy development with the basis on the same underlying values. The concept integrates five subsystems to succeed with project execution and implementations by following a standardized methodology. The EEM road map eases the achievement of flawless operations at the lowest lifecycle cost. The five subsystems are presented below and further explained at the second half of this section (McCarthy, 2017):

1. Design and performance management
2. Specification and LCC management
3. Project and risk management
4. Project governance
5. Best-practice design book

The purpose of implementing EEM includes reducing the risk of getting into project delivery pitfalls and making better decisions. The method is not only aimed at evaluating the best procurement but is trying to capture potential problems as early as possible in the process. This is because it is usually easier and cheaper to handle these beforehand. The project steps are divided into three sections: define, design and refine. Define aims to 'to get the right design' by developing conceptual project ideas before creating a high-level design where the goal is to get approval of funding. The cost curve depends on life cycle cost (LCC), i.e., capital expenses in addition to progressing operational expenses. Spending plans are set with the desire that continuous improvement tools will be applied during the venture to distinguish approaches to decrease LCCs and increment venture an incentive in target zones. These objectives are incorporated as a major aspect of the financing endorsement process. Next section addresses 'to get the design right' by doing a more detailed design that leads to decisions about supplier selection and setting a project planning. Within the same section, preparations for site implementation and the procurement process of the equipment process. The final step involves 'to get design gains' which is summed up as installation of equipment by positioning and merging with existing equipment before validating the process capability. (McCarthy, 2017)

3.3.3 Cost Parameters

There are a variety of ways to make cost estimates for equipment. Kampker et al. (2013) for example, choose to divide life-cycle costs into two categories: operating expenses and adaptation cost. On the other hand, Heilala et al. (2008) chooses to distribute total costs through three subcategories: fixed cost, recurring cost, and yield cost. The cost structures are usually differentiated according to company-specific preferences and industry standards and thus there is no general methodology to follow (Heilala, et al., 2008).

3.3.4 Non-Financial Returns and Parameters

Non-financial returns and parameters reflect all factors that cannot be transmitted to cash-flows. One way of evaluating these involves a linguistic scale where decision-makers themselves sets meaning (values) of any word (linguistic variable) based on the firms' preferences (Abdel-Kader, 1999). Nelson (1986) gives examples of other non-financial return parameters and introduces a technology assessment score model that considers status, emphasis, impact, condition, suitability, and age of the investments in relation to current equipment.

Table 8 – Capital Prioritization Techniques

Method	Description	Source
Payback Period (PP)	Estimates the time required for the investment to reach breakeven	(Fechter, et al., 2019; Kahraman & Tolga, 1998; Abdel-Kader, 1999; Bayou & Jeffries, 2006)
Discounted Payback Period (DPP)	Estimates the time required for the investment to reach breakeven but discounted yearly	(Kahraman & Tolga, 1998)
Discounted Cash Flow (DCF)	Estimates the projects generating cash flows and discounts these on an annual basis.	(Jiao, et al., 2006)
Net Present Value (NPV)	Calculates the difference between the present value and the cash flows over a period	(Fechter, et al., 2019; Heilala, et al., 2008; Abdel-Kader, 1999; Andersen, et al., 2018; Bayou & Jeffries, 2006; Mac-Stravic & Boucher, 1992)
Internal Rate of Return (IRR)	Calculates the interest rate which explains the net present value of all the cash flows	(Fechter, et al., 2019; Kahraman & Tolga, 1998; Heilala, et al., 2008; Bayou & Jeffries, 2006)
Total Cost of Ownership (TCO)	Calculates the total cost associated with the equipment over a period	(Heilala, et al., 2008)
Return on Investment (ROI)	Calculates the percentage as net benefits of the investment	(Abdel-Kader, 1999; Bayou & Jeffries, 2006)
Life-Cycle Cost (LCC)	Estimates the total cost for the equipment over its life cycle	(Fechter, et al., 2019; Heilala, et al., 2008; Kampker, et al., 2013)
Activity-Based Costing (ABC) *(Accounting)*	A cost monitoring system for tracking costs related to activity levels.	(Fechter, et al., 2019)

3.3.5 Handling the Uncertainty

Most of the articles in the review uses a stochastic and/or real options theory approach to handling uncertainty. Stochastic methods comprise a random probability distribution or pattern that could be statistically analyzed but may not generate a precise prediction (Lexico, 2019). Real options theory draws parallels between the valuation of the financial options to the real economy by choice available regarding a tangible asset e.g., not a financial instrument (Xiaoguo & Min, 2012). The benefits of a real options approach involve bypassing the discounted cash flow analysis-based valuation methods, which ignores the upside of flexibility (Jiao, et al., 2006; Xiaoguo & Min, 2012).

Demand uncertainty and product mix uncertainties involve expected fluctuations of total sales and the relationship between products or/and product families. The uncertainty stems from the gap to the state of perfect information. Renna (2017) creates a hypothetical uncertainty of market demand by Monte Carlo simulation to determine the manufacturing strategy that needs to be implemented by the firm. Monte Carlo reproduction is a modernized numerical method that permits individuals to represent chance in quantitative investigation and dynamic (Renna, 2017). Multivariate demand distribution with linkage to a traditional newsvendor model could be used and by incorporating product, resource, and demand differentiation through price and cost vectors with a technology matrix. Rashidi-Bajgan, et al. (2010) suggests that stochastic and fuzzy programming approaches could be used in these scenarios in order to deal with uncertainty of future demand in capital budgeting problems.

Internal uncertainties include machine breakdowns and process-related losses. Heilala, et al. (2008) handles this by combining system and component-based simulations for cost and performance for determining and understanding design effectiveness from a lifetime perspective. Equipment uncertainty involves feasibility and expected maturity level for upcoming products. Abdel-Kader (1999) points out that all projects should be analyzed on the basis of risk and sensitivity analyzes as well as the origin of the risks and proposes to embed either quantitatively using fuzzy numbers or qualitatively using a linguistic scale. Kampker, et al (2013) evaluates investment decisions by using a four pronged approach where a set of potential future scenarios of the system's life cycle before evaluating return on flexibility and return on automation to aforementioned scenarios.

3.4 Manufacturing Readiness Level

Due to secrecy, the Manufacturing Readiness Level (MRL) will be explained from a general perspective and not from the focal company's own template and processes.

MRL can be used in the early stages of a product development process to determine the readiness level of the manufacturing processes that exist in the factory. This to monitor the uncertainties and determine what level of focus different parts should get. For example, in a new product development process, the MRL can be both low and high depending on how the development approach from the developer has been chosen. If the new product requires a new technology that does not exist inhouse and takes too long time to develop, maybe other manufacturing alternatives need to be assessed (Madison, et al., 2015; Islam, 2010). Opportunities like outsourcing or working with a company that implements the production line inhouse can be used (Madison, et al., 2015). If the developer instead chooses a technology that can be mastered inhouse the MRL level will be higher and the production can be held inhouse. The scale which can be seen in Madison et al, (2015) can be adjusted to be company-specific in order to match the need better. The importance is to be aware of the maturity level and what actions need to be taken in order to secure the right decision.

Table 9 - Manufacturing Readiness Levels (Madison, et al., 2015)

Level	Definition	Technology transfer to the Manufacturer
1	Basic manufacturing implications identified	-
2	Manufacturing concepts identified	Statement of work identifies a manufacturer will be used
3	Manufacturing proof of concept developed	Request for information/qualification released. Manufacturing partner Identified
4	Laboratory manufacturing process demonstration	Industrial capabilities planning Proof of concept feedback
5	Manufacturing process development	Production system components P&ID Reliability Studies
6	Critical manufacturing processes prototyped	Manufacturing Drawings Production system or sub-systems.
7	Prototype manufacturing system	-
8	Manufacturing processes maturity demonstration	-
9	Manufacturing processes proven	

4 Findings

This chapter outlines what was found from the case study which was carried out through interviews and document study. It presents how the focal company use different methods and what methods that where further explored for the study

4.1 General

The basis for the investment process is a systematic way of requesting funds for new projects. The initiator of the project's intention is to enhance the performance of the firm to accomplish the organizations overall goals. The project could have a variety of objectives e.g. increasing capacity, rationalization, machine exchange and improving the work environment. When acquiring production equipment, an implementation concept is applied, the concept is called early equipment management (EEM), which is an extraction from the lean manufacturing philosophy.

The way of working can generally differ between the different sites, but the underlying standardized evaluation process is used within the group. Generally, each site has a goal of delivering a certain volume, or capacity, that meets demand in the final assembly. In connection with major product introductions or volume changes, the current situation is investigated by means of a gap analysis. In this process, the current situation is reviewed and then compared with the future situation to find out what efforts need to be made. In today's process, many investments are linked to product introductions. In these evaluations, for example, machine readiness level is used to evaluate the production technology maturity of machines and decide whether the machine can produce, needs to be rebuilt or procured. There is a global department that manages technologies or machines that have a low degree of maturity, so the descriptive approach only applies to investments that are ready to be used during industrialization phases. If a replacement process of equipment is carried out, the company evaluates over capacity fluctuations in a few years' time so as not to set too low capacity levels. When initiating a new project, the initial cost of investment should be estimated at a value of +/- 30%, followed by tapered investment gates where the variation in the budget request takes place at +/- 10%. The investment decision occurs in different hierarchical levels of the organization depending on the level of the monetary amount requested.

4.2 Calculations

When calculating the financial impact, the focal company uses the 'life cycle costing' method. In this calculation, the firm tries to include as many factors as possible that affect the equipment costs. In any case, an estimate is made and, depending on initial differences, a decision is made whether the controllers feel comfortable with the data or to decide if more data needs to be collected. There may be systematic effects that affect the calculations where capacity in bottlenecks contributes to higher throughput or machine-individual aspects such as energy consumption or the relevance of other key performance indicators. At the focal company, the evaluation material is always made on the sites, even if the decision is at another hierarchical level. A deeper explanation of LCC can be found in chapter 3.3.

4.3 Prioritizations

In the priorities between which investment decision to make, the organization always assumes which alternatives are 'on the table' where priority is given to 'best business'. The goal is to determine whether the focal company evaluates operational impact figures or if there are other evaluation methodologies. Overall, it is the financial impact that has the most influence on the decisions and where individual key performance indicators are not necessarily used unless it affects the life cycle costing calculation. When it comes to rationalization investments, there is a rather high demand for quick repayment as the risk is considered higher to replace something that works.

4.4 Risk Assessment

In most cases, the risk analysis is carried out solely by the controllers, thus, the operation department is not providing any risk-assessments. In this process, the focal company weighs the pros and cons and considers various scenarios that may occur around the machine. It also evaluates how well the suppliers are in delivering spare parts and maintenance that are considered in the overall evaluation. This is especially true when spare parts sales cease, which can usually be solved but contribute to great uncertainty. Even too high a price is seen as a risk factor in that error calculations can lead to the project resulting in a loss transaction. In replacement processes, use internal replacement policies to evaluate risk.

4.5 Manufacturing Readiness Level

Looking forward it came up during an interview that to handle the future mapping of new components a combination of Manufacturing Readiness Level (MRL) and an element were used to create a matrix. A document containing the matrix where obtained and studied. MRL has been further explained in the literature review in chapter 3.4.

5 Performance Indicators and Reconfigurability

This chapter consists of three different chapters that compile and group the different metrics through similarities, a process of standardization in relation to ISO-22400:2, and adjustments to new data points and key performance indicators.

5.1 Grouping and Selection of the Key Performance Indicators

To minimize duplicates and interweaves, the data from key performance indicators needs to be cleared to a common foundation. The grouping resulted into seven main categories of system capability, productivity, flexibility, quality, cost, risk, and people. These categories were named based on the commonality were chosen. Underneath each heading, the found performance indicators groupings are explained.

5.1.1 System Capability

System capability is the ability of a system to execute a task or action. To this category, the key performance indicators which are addressing ‘manufacturing system capabilities’ have been grouped into eight measures where Xiaowen, et al.’s (2009) definition of changeover time have been grouped with reconfiguration time because of commonalities, seen in Table 10.

Table 10 - System Capability Aspects

System Capability Aspects
• *Process capacity* provides insights in a firm’s theoretical ability to deliver and satisfy different production needs. (Xiaowen, et al., 2009) • *Balancing* is the ability to adjust process times and workloads between machine groups or individuals to reduce production rate losses. (Xiaowen, et al., 2009) • *Diagnosability* is the ability to identify and address product quality and failures (Xiaowen, et al., 2009). • *Set-up time* is the introduction time of a new product within a product family and involves retooling, operator reassignment and machine set-up. (Abdi, 2009) • *Ramp-up time* explains the period from completed initial product development to maximum capacity utilization. (Xiaowen, et al., 2009; Garbie, 2014) • *Reconfiguration time* is used to measure the time of a configuration from current state to desired state. (Mittal & Jain, 2014) • *Manufacturing lead time* explains the time required or used cycle time to produce a certain product throughout parts of or the whole manufacturing system. (Garbie, 2014) • *Mean time between failures* is the average time between two system failures. (Xiaowen, et al., 2009)

System capabilities measure capabilities that correlate with the X definition of manufacturing requirements such as rebuilding to offer more variants where set-up time, ramp-up time and reconfiguration time measure the capability between two predetermined modes. Lead time can be linked to increased rewards and sonics contribute to a relatively lower price. Shorter lead time has a direct link to manufacturing lead time which measures performance within the manufacturing unit. The capacity to handle volume is measured through process capacity that measures the system's potential ability to deliver total volume and reduce the cost per unit and thus contribute to a lower price.

5.1.2 Productivity

Productivity is related to the input and output ratio which explains the efficiency and effectiveness of manufacturing aspects according to Tangen (2002). Effectiveness can be measured by the ability of producing products and thus explained as the production rate according to Garbie (2014). Another term with the same explanation is system productivity but hence the word productivity is not being equivalent to Tangen's definition of productivity, the production rate is considered to be a more relevant terminology (Xiaowen, et al., 2009; Tangen, 2002). System utilization is used from Garbie's (2014) perspective to average all machine utilization degrees and Abdi (2009) have a similar approach to utilization, hence, both will be categorized with equipment utilization. Mittal & Jain (2014) defines availability as the probability of the machine being available for usage. Another terminology used for that is system availability (Xiaowen, et al., 2009) and can be seen in Table 11.

Table 11 - Productivity Aspects

Productivity Aspects
• *Production rate* represents the produced quantity in unit time (Garbie, 2014; Xiaowen, et al., 2009)
• *Equipment utilization* defines the degree of which processing units are being used. (Xiaowen, et al., 2009; Abdi, 2009; Garbie, 2014)
• *Availability* is the probability which the system status is ready to be used or operated. (Xiaowen, et al., 2009; Mittal & Jain, 2014)

Productivity aspects involves the use and productivity of external and internal resources but also the company's ability to eliminate unnecessary waste. By increasing the productivity, defined by Tangen (2002), key functions as input and output in the manufacturing system will be targeted to achieve the manufacturing environment goal. The ability defines how achievable low cost, thus prices, are in the manufacturing systems. The rate of production is a measure of the frequency of the number of products flowing out of the system. By the definition of Xiaowen (2009) this number describes the ability to produce volume which, according to the same article, is a reward which must be set in relation to low price and leads to economies of scale. Equipment utilization evaluates the productivity of the equipment the company uses, and availability describes a company's ability to eliminate machine disruptions in production. Therefore, these KPIs are relevant to further evaluate in the analysis.

5.1.3 Flexibility

Flexibility relates to the manufacturing goal of 'more variants' and 'low and fluctuating volume' accordingly to the manufacturing demands provided by Bi, et al., (2008) and thus it is relevant to elaborate upon. Flexibility is a countermeasure for uncertainty and can be described as the ability to handle those. Xiaowen et. al's (2009), Abdi (2009) and Garbie (2014) have stressed the importance of measuring the flexibility in three perspectives that has been named product (mix) flexibility, production volume (demand) flexibility and material handling flexibility, see Table 12.These relates to the overall goal of reconfigurability but addresses certain focuses in a manufacturing setting. For some companies, product flexibility is a necessity, but volume might remain the same. Therefore, the key performance indicators need to be separate to handle the different types of uncertainty and can be seen in Table 12.

Table 12 - Flexibility Aspects

Flexibility Aspects
• *Product (mix) flexibility* measure aims to quantify the ability of handling product variations within a product-family by modular extent of machines and tools. (Xiaowen, et al., 2009; Abdi, 2009; Garbie, 2014)
• The *volume flexibility* aims to explain the firm's ability to handle fluctuations in market demand and order volume. (Xiaowen, et al., 2009; Abdi, 2009; Garbie, 2014)
• *Material handling flexibility* is the ability to handle quick and efficient changes in different material handling flows. (Xiaowen, et al., 2009; Abdi, 2009; Garbie, 2014)

Product (mix) flexibility can be explained as the manufacturing's systems ability to produce various product family. Thus, it can be related to Abdi's (2009) definition of 'new product introduction', Xiaowen et. Al.'s (2009) equipment reconfigurability and Abdi's (2009) 'variety' because of commonalities. These together aims to measure and quantify the ability of handling product variations within a product-family by modular extent of machines and tools. The volume flexibility has been combined with logistic reconfigurability by Xiaowen et. al's (2009) and Abdi's (2009) 'volume' and 'mobility' where the volume flexibility aims to explain the firm's ability to handle fluctuations in market demand and order volume. Material handling flexibility has been grouped with Abdi's (2009) term 'volume' and Xiaowen et. Al.'s (2009) term 'process reconfigurability'. Material handling flexibility has the ability to handle quick and efficient changes in different material handling flows.

5.1.4 Quality

Quality is a broad term and can be defined as several elements within manufacturing terminology. Commonly, through the literature studies conducted within the field of RMS it could be seen in (Garbie, 2014; Abdi & Labib, 2004; Abdi, 2009; Mittal & Jain, 2014) that the articles had chosen to focus either on product quality or process quality. Still there is no systematic way of evaluating the reconfigurability of each product family and the quality of each configuration (Abdi & Labib, 2004).

Quality can be defined either as the 'fitness for use' but could also be defined as the 'conformity of requirement'. Hence, the system responsiveness is another meaning for quality (Mittal & Jain, 2014). By calculating the average value of reliability and utilization, Jain and Mittal (2014) considers the value as the responsiveness of a system. Abdi (2009) defines quality as four criteria's 'convenience of use', 'reliability', 'accuracy' and 'compatibility' where all needs to be fulfilled for the system to act smoothly but is not defining the concepts in more depth. Both Garbie (2014) and Mittal and Jain (2014) has a similar approach but they have taken a perspective and not defined several elements within product quality. Garbie (2014) measures the quality through looking at the scrap rate at different times during the production and Mittal and Jain (2014) looks at the reliability and utilization in order to get a number of the quality. Abdi and Labib (2004) investigates the quality measurements in terms of final product quality. Reconfiguration quality became an summary from the Abdi (2009) and Mittal & Jains (2014) definition of quality in relation to reconfigurable manufacturing systems and can be seen in Table 13.

Table 13 - Quality Aspects

Quality Aspects
• *Reconfiguration quality* involves the machines convenience of use, reliability, accuracy, compatibility, and utilization while doing configurations. (Abdi, 2009; Mittal & Jain, 2014) • *Product quality* is a summary of the final product quality and the product quality which focuses on the outcoming quality of the of the production system. (Abdi & Labib, 2004; Garbie, 2014)

Connecting to the manufacturing requirements, quality makes it possible to decrease lead time and handling more variants. This because of increased quality leads to more parts produced and a more stabilized production. A stabilized production does not necessary give you a shorter lead time, but it will give the possibility to improve through different methodologies. Quality also influences low and fluctuating volumes and low price, but the biggest impact is on the short lead time and more variants.

Risk

Risk is an aspect that has been used in several articles and aims to evaluate whether the probability of setbacks is higher in different parts of their production process. The one who defines the concept most extensively is Xiaowen, et al. (2009) which divides the category into three parts, technological risk, organize risk and market risk and can be seen in Table 14.

Table 14 - Risk Aspects

Risk Aspects
• Technology risk addresses the risk of implementing new technology implementation and integration (Xiaowen, et al., 2009) • Organize risk is the reliability of management and system construction processes and its ability to meet the set requirements. (Xiaowen, et al., 2009) • Market risk is used to explains the handling dynamic changes in demand fluctuations and customer customization needs. (Xiaowen, et al., 2009)

Risk has no connection to the overall objectives of manufacturing as defined by the manufacturing requirements of Bi, et al. (2008). Instead, it should be seen more as a counterparty to flexibility and at what level external and internal uncertainty affects the manufacturing system. However, uncertainty is an important part of assessing flexibility and has an impact on investment decisions. Thus, this category will not be further addressed in this chapter.

5.1.5 People

People behavior (PB) is hard to measure related to a product because of its qualitative nature and its multidimensional values (Garbie, 2014). Although, some measurements can be used as Number of people hiring (PBH), Number of people who reject reconfiguration (PBR), the amount of motivation related to a pay raise (PBM) and number of fired people (PBF) (Garbie, 2014).

5.1.6 Environment

Environmental friendliness can be both internal and external when it comes to measurements. When measuring the manufacturing system, it is often talked about as internal measurements and are thus related to 'optimal use of resources', 'security' and 'friendly interface' (Xiaowen, et al., 2009). As its not contributing to the directly in form of any monetary value it will be disclosed from this study.

5.1.7 Summary

A summary of the grouped key performance indicators with high relationship to the manufacturing requirements can be found in the following Table 15 where relationship according to the analysis and manufacturing requirements can be found in Table 5.

Table 15 - Key Performance Indicators with High Relationship

High Relationship	
Process capacity limits	*System capabilities*
Balancing	
Set-up time	
Ramp-up time	
Reconfiguration time	
Lead time	
Diagnosability	
Mean time between failures	
Production Rate	*Productivity*
Equipment Utilization	
Availability	
Product (Mix) Flexibility	*Flexibility*
Production Volume (Demand) Flexibility	
Material Handling Flexibility	
Reconfiguration quality	*Quality*
Product quality	

The following metrics, seen in Table 16, do not qualify for manufacturing requirements but are considered to have an impact on investment decisions and will thus be relevant to the decision support model but should not necessarily evaluate performance.

Table 16 - Key Performance Indicators with Medium Relationship

Medium Relationship	
Technology risk	*Risk*
Organize risk	
Market risk	

As some metrics deviate from the general theme and are not used in calculating investment models, the following indicators, seen in Table 17, are not considered to be applicable to meet manufacturing requirements or be further developed into decision basis and hence dropped from the analysis.

Table 17 - Key Performance Indicators with Weak Relationship

Weak Relationship	
Hiring	People
Rejection	
Motivation	
Fired	
Operator skills	
Safety	
Security	Environment
Friendly Interface	

5.2 Process of Standardizing

To create understanding and ease the implementation of key performance indicators, an ISO standard was coordinated to find commonalities with the chosen parameters. The mapping involved the selected key performance indicators on the Y-axis and the ISO 22400 standard on the X-axis. The mapping was being done by categorizing commonality in three classes: ‘Directly applicable’ (DA), ‘Requires adjustments’ (RA) and ‘Not applicable’ (NA). These are seen in Appendix 1.

When calculating system changes for an investment, it is important to compare numbers of equal weight. Hence, time data needs to be on the same scale. Since it can be assumed that it is more likely that the data is theoretically calculated than the actual output outcome, planned times are preferred compared to actual times in these calculations.

5.3 Data Points and Level of Collection

The underlying data points for the key performance indicators needs to be mapped and can be seen in Table 18. The data points used in these calculations are 'actual production time' (APT), 'actual unit busy time' (AUBT), 'actual order execution time' (AOET), 'produced quantity' (PQ), 'planned busy time' (PBT), 'good quantity' (GQ), 'failure event' (FE), 'operating time between failure' (TBF), 'planned unit set-up time' (PUST), 'process capacity limit' (PCL), 'planned ramp-up time' (PRUT) and 'planned reconfiguration time' (PRFT).

Table 18 – Key Performance Indicators and Data Points

Key Performance Indicators	Data Points
Allocation efficiency	$\frac{AUBT}{PBT}$
Availability	$\frac{APT}{PBT}$
Mean operating time between failures	$\frac{\sum_{i=1}^{i=FE} TBF}{FE+1}$
Quality ratio	$\frac{GQ}{PQ}$
Throughput rate	$\frac{PQ}{AOET}$
Utilization efficiency	$\frac{APT}{AUBT}$
Lead time	LT
Process capacity limits	PCL
Set-up time	$PUST$
Ramp-up time	$PRUT$
Reconfiguration time	$PRFT$

In addition to creating an understanding of the underlying values in the indicators, it also demonstrates which indicators interact with each other and what information is needed to be collected. The matrix in Appendix 3 illustrates a common point of contact between 'availability' and 'utilization efficiency' through 'actual production time' (APT). Moreover, 'allocation efficiency' and 'utilization efficiency' both use 'actual unit busy time' (AUBT). The data point 'planned busy time' (PBT) is included in both 'availability' and 'allocation efficiency'. Furthermore, it can be read that 'produced quantity' (PQ) is used as a basis for calculating 'quality ratio' and 'throughput rate'.

If a system is built that requires a large amount of data and there is no efficient data collection process integrated with the system, it creates a workload to manually collect the data. This helps to limit the number of data points to the highest general level, without losing validity. Through an evaluation process and the guidelines from the ISO standard, different hierarchical levels were selected for the different data collection points. In Appendix 3 page 2. explains that within the line level five different data points should be collected: actual order execution time, actual production time, good quantity, produced quantity and failure event. At the cellular level, actual unit busy time, operating time between failure, planned unit set-up time, planned ramp-up time and planned reconfiguration time. At the machine level, busy time, equipment production capacity and process capacity limits are found.

6 Complementing Key Performance Indicators with new ones based on Reconfigurability Characteristics

In this chapter KPIs that were not able to be matched with the ISO – standard will be develop and defined. Each KPI will first be defined and compared to current literature and then a formula will be created or added to the KPI. Each KPI will be described through an ISO – standard template.

From the previous chapter, the following key performance indicators were not compatible to be adjusted to any ISO-standard and hence needs to be developed and defined, Table 19:

Table 19 – Non-Standardized Key Performance Indicators

Key Performance Indicators that Needs to be Defined
• Product (mix) flexibility
• Production volume (demand) flexibility
• Material handling flexibility
• Reconfiguration quality
• Diagnosability

Product (mix) flexibility wants to measure the manufacturing systems possibility to adjust within a part family without a major reconfiguration according to Garbie (2014). As RMS has focused on using configuration to switch between product families (Andersen, et al., 2018) the aim should be to handle configurations between product families with the smallest incremental effect as possible on the manufacturing system. Therefore the definition of Garbie (2014) will form the foundation of the KPI but will be adjusted to fit better into the definition of RMS in chapter 3.2.

The new adjusted KPI is named product family flexibility and has the purpose to show how good the manufacturing system is on handling different product families and the future introductions of products. It requires the manufacturing system to be modular, has standardized interfaces and the ability of diagnosability discussed by (Koren, et al., 1999; Mehrabi, et al., 2000; Napoleone, et al., 2018b). These are key functions within an RMS, although some of them are not easy to measure within a manufacturing system, hence the KPI will focus on evaluating the manufacturing system's ability to handle configurations between product families.

Production volume (demand) flexibility has the purpose to measure the flexibility in the system (machines) in increasing and decreasing the volume depending on the changing demand coming from the market (Garbie, 2014). As shown earlier in chapter 3.3.1. it can be seen that scalability is highly dependent on the other characteristic's modularity, diagnosability and integrability (Napoleone, et al., 2018a). Thus, the level of complexity on how to manage the scalable characteristics increases. As it does not depend solidity on its own, an increased need for structure and clarity within the manufacturing system is needed. Through designing the manufacturing system following a structured model as one Rösiö & Bruch (2018) has designed the possibility of achieving structure and clarity can increase.

Key factors for a manufacturing system to be scalable is through achieving the influencing characteristics goals. Hence important parts to achieve is modularity, standardized interfaces (Koren, et al., 1999; Mehrabi, et al., 2000; Napoleone, et al., 2018b), quick identification of quality or reliability errors (Mehrabi, et al., 2000) and components ability to be removed or integrated (Koren, et al., 1999; Mehrabi, et al., 2000). Hence the production volume (demand) flexibility can be related to scalability. As mentioned there are key influencing elements on characteristics scalability but ElMaraghy (2006) has defined its own key factors for scalability to be the ability to have a balanced line and to work with the amount of shift/workers. To formulate a KPI the foundation of production volume (demand) flexibility will be used but modified to match the definition above.

Material handling flexibility has the purpose to measure the system's ability to handle reconfiguration when a new material flows and material flow capacity when changing from product A to B (Garbie, 2014). This is similar to production volume (demand) flexibility which handles the scalability of the system. The factors influencing material flows and capacity can be closely related to the same characteristics as mentioned for production volume (demand) flexibility but it will have an input on how well the line will work. Whereas production volume (demand) flexibility will have an effect, directly on the line. Material handling flexibility does not need to be greater than the throughput rate for the line it goes to. This to avoid unnecessary capacity that is not utilized. Still, the system should have the ability to follow the fluctuations in both product mixes and volumes, this creates a high demand om the system to adjust quickly and efficiently. Key factors in material handling can be defined as planning, standardization, ergonomic, flexibility, simplification, gravity, layout, cost, maintenance, unit load principle, space utilization principle, system principle, automation principle, environmental principle and life cycle cost principle (Aized, 2010). The goal should be to have optimized each principle so it in an economical and sustainable way fits the factory.

The formula will be like production volume (demand) flexibility but will be adjusted with a limitation to max capacity compared to the line.

Reconfiguration quality is perceived by different perspectives but the purpose to evaluate the quality of the manufacturing system and its components in terms of quality. Mittal and Jains (2014) interpretation of the concept does not correlate with any characteristics and is more relatable to the manufacturing requirements of production with high resource efficiency. However, Abdis (2009) sub-categories of quality have similarities to the characteristics. Compatibility has links to the ability of customization where it is possible to use same tools or machine for an operation (Röisö, et al., 2019). 'Convenience of use can' be interpreted as anything that simplifies work and could be linked to the goal of modularity section where the underlying goal is to standardize modules interfaces and components integration of hardware and software. These objectives should decrease number of work steps, time, and increase integration rules that enhances the abilities of convertibility, scalability and diagnosability. Reliability and accuracy are aspects that could not be enhanced to a characteristic but are still relevant accordingly to manufacturing requirements.

Diagnosability and its impact on reconfigurable manufacturing systems is one of the specified characteristics. However, from the literature review it was found that Mehrabi (2000) demonstrates that the ability of diagnosability by its involvement of how quickly one identifies a machine failure and isolate the defect products for reaching customers. As Napoleone et al. (2018a) claims that another involves the ability to correct the fault quickly in an operational context.

6.1 Defining the Performance Measurements

The new performance measurements that have been defined in the earlier chapters and need to be explained and described. The new KPIs that are created in this chapter are created with the purpose of completing the model with elements that should cover different aspects of an RMS as defined by Bi, Lang, Shen and Wang (2008). Below new KPIs will be described and defined to support the current model with KPIs to measure.

Product (mix) flexibility

As defined above product (mix) flexibility wants to measure the manufacturing system's ability to reconfigure between different product families (Garbie, 2014). To measure the product flexibility, it is needed to look if the machine can handle all product families within its technical or economical lifetime. If it´s achievable it can be said that a high level of product mix flexibility has been achieved. This, because the machines handled all different product families when it was in production. Hence the machines need to be replaced or updated after the lifetime has run out. The KPI definition can be seen in Table 20.

Table 20 - Product (mix) Flexibility

KPI Definition	
Content	
Name	Product (mix) flexibility (PmF)
Description	Measure the system's ability to reconfigure between different product families
Scope	Unit
Formula	PmF = 100 x (Technical or economical lifetime < (# of product families that can be used) / (total # product families that are planned in the technical or economical lifetime))
Unit of measure	%
Range	Min: 0, Max: 100
Trend	The higher the better
Context	
Timing	On demand
Audience	Supervisor
Production Methodology	Discrete

Production Volume (demand) Flexibility

In production volume (demand) flexibility, the goal is to measure the manufacturing systems ability to adjust to the fluctuating volumes (Garbie, 2014). By measuring the ability to reconfigure the system and how long it takes to ramp-up the production to its full capacity. It can be measured how well we can adapt to changes rapidly. The most suitable times are decided on what is suitable to manage the current production. A good way of measuring the system's ability to reconfigure is through a definition created by Rösiö, et al., (2019) and has the following elements: smallest incremental capacity and existing capacity. The KPI definition can be seen in Table 22 and the definition of data points in Table 21.

Table 21 - Definition of Smallest Incremental Capacity and Existing Capacity

Data point	Definition
Smallest incremental capacity	How much can the capacity be increased stepwise in order to meet the actual demand.
Existing capacity	The capacity existing in the factory at the moment.

Table 22 - Production Volume (demand) Flexibility

KPI Definition	
Content	
Name	Production volume (demand) flexibility (PVdF)
Description	Measure the system ability to adjust to fluctuating volumes.
Scope	Unit
Formula	PVdF = 100 x (1 - (Smallest incremental capacity / Existing capacity)
Unit of measure	%
Range	Min: 0, Max: 100
Trend	The lower the better
Context	
Timing	On demand
Audience	Supervisor
Production Methodology	Discrete

Material handling flexibility

As defined in the previous chapter the aim of material handling flexibility is to measure the time it takes to reconfigure new material flows or capacity flows. Although there are several parameters influencing the material handling flexibility KPI and it needs to be defined in such a way that makes it handleable, yet justifiable for evaluating the production.

Therefore, important parts are the way the logistic flow is constructed to work, is it built modular, is it easy to maneuver and how well can it adjust to fluctuating volumes. This results in how well the routing of reconfigurability, software and hardware are able to be performed, hence it needs to be evaluated to see how well the production can handle material flow changes.

A possible way of measuring the routing of the material handling is through evaluating the reconfigurability as described by Garbie (2014). Other alternatives and combinations of others have been investigated but to get a clear structure it's been chosen to proceed with Garbie (2014) definition Table 24. Material handling flexibility is calculated through the following Equation 1 and the coherent data points in Table 23

Equation 1 - Material Handling Flexibility

$$\mathrm{MHF(t)} = \sum_{i=1}^{n(t)} x(t)_i\, \mu(t)_i v(t)_i \varepsilon(t)_i \beta(t)_i$$

Table 23 - Definition of Data Points within Material Handling Flexibility

Data point	Definition
x(t)	is the number of material handling components at time t
μ(t)	is the maximum unit load quantity factor based on the capacity of the equipment at time t
v(t)	is the equipment speed based on the normal operating speed of the equipment at time t
ε(t)	the equipment loaded travel factor at time t.
β(t)	is the relative rerouting cost indicating the ability of equipment re-configuration time t.

Table 24 - Material Handling Flexibility

KPI Definition	
Content	
Name	Material handling flexibility (MhF)
Description	Measure the system ability to adjust to fluctuating volumes.
Scope	Unit and process-unit
Formula	MHF(t)= ∑x(t)μ(t)v(t)ε(t)β(t)
Unit of measure	Time (sek/min/hour)
Range	Min: 0, Max: xx
Trend	The lower the better
Context	
Timing	On demand
Audience	Supervisor
Production Methodology	Discrete

Reconfiguration quality

Reconfiguration quality already has a definition and according to Mittal and Jain (2014) which is the mean of reliability of utilization. The reliability measurement will be defined as the product probability of an equipment performing its intended function for a stated period of time under certain specified conditions and is calculated differently based on the manufacturing layout where a series involve single machine in each step. Seen in *Equation 2*.

Equation 2 - Reliability of Machines in Series

$$\text{Reliability}_{\text{series}} = \prod_{t=1}^{n} R_i$$

The following measurement is used if number of machines at each configuration are more than one, called parallel. Seen in Equation 3.

Equation 3 - Reliability of Machines in Parallel

$$\text{Reliability}_{\text{parallel}} = 1 - \prod_{t=1}^{n} (1 - R_i)$$

Where n is number of machines and R_i is the i^{th} configuration.

The term utilization in Mittal and Jain (2014) has the same technical definition as the ISO-standard but the article uses processing time of a configuration and production time to define the utilization where the standard calculates the ratio between actual production time (APT) and the actual unit busy time (AUBT), giving the following Equation 4 accordingly to the standard (ISO, 2014):

Equation 4 - Utilization Efficiency

$$Utilization\ efficiency = \frac{APT}{AUBT}$$

The section is summed up by developing the final definition explained in Table 25.

Table 25 - Reconfiguration Quality

KPI Definition	
Content	
Name	Reconfiguration quality
Description	Measures the reconfiguration quality of a production process by an average value of reliability and utilization efficiency. Reliability is the product of the probabilities of an equipment performing a task at a certain time and the utilization efficiency is based on the ratio between actual production time (APT) and actual unit busy time (AUBT).
Scope	Unit and process-unit
Formula	$Reconfiguration\ quality = \frac{R + UE}{2}$
Unit of measure	%
Range	Min: 0, Max: Unlimited
Trend	The higher, the better
Context	
Timing	On-demand, periodically
Audience	Supervisor, Management
Production Methodology	Discrete, Batch

Diagnosability

With background from the previous chapter, the assumption is made that diagnosability involves three parts such as fault detection, fault isolation and fault identification. Thus, a measurement number for diagnosability should address one involving all three aspects of a common figure by combining three equal proportions. A performance figure for fault detection should reasonably involve how often the product quality is observed and/or tested. The assumption is that problems will be detected more quickly if all products are examined than if a lower frequency is applied. The following Equation 5 is being used for fault detection and its data points is defined in Table 26

Equation 5 - Fault Identification

$$Fault\ identification = \frac{IP}{PQ}$$

Table 26 - Definition of Inspected Part and Produced Quantity (ISO, 2014)

Data points	Definition
Inspected part (IP)	"An inspected part must be the count of individual identifiable parts, e.g. by serialization, which was tested against the quality requirements."
Produced quantity (PQ)	"The quantity produced must be the quantity that a work unit has produced in relation to a production order."

To measure the ability to isolate faults, the KPI 'actual to planned scrap ratio' from the ISO standard would use percentage as a unit of measure and demonstrate the ratio between the quantity of actual scrap and planned scrap quantity. This metric is considered relevant for measuring how the system isolates and manages machine failures by evaluating the proportion of good products that arise in connection with the process. A lower number would thus indicate a better ability to isolate the problem. The problem with this way of reasoning should therefore be that it measures total quality levels which should not reflect one's ability for diagnosability. Another way to address this phenomenon could be to use the actual to planned scarp ratio instead, based on the outcome of scrap levels with planned rate for the same period. Seen in Equation 6.

Equation 6 - Actual to Planned Scarp Ratio

$$Actual\ to\ planned\ scrap\ ratio\ (APSR) = \frac{SQ}{PSQ}$$

How quickly one addresses the problem is considered fault identification. The literature of Rösiö, et al. (2019) emphasizes, among other things, working with Poka Yoke which is a working method but is not a metric that can be compared. Thus, the metric should be designed for how quickly the problem is addressed and this should be related to the amount of time spent between the problems to make the key figure generalizable between different types of industries. The ISO standard (2014) defines these terms as 'time to repair' and 'mean time between failures' and the citation for these notions can be seen in Table 27

.

Thus, the following Equation 7 is given by the ISO-standard.

Equation 7 - Fault Detection

$$Fault\ detection = \frac{MTTR}{MTBF}$$

Table 27 - Definition of Time to Repair and Mean Time between Failures (ISO, 2014)

Data points	Definition
Time to repair (TTR)	"Mean time to repair (MTTR) is the average time that an item required to restore a failed component in a work unit. The mean time to repair is calculated as the mean of all time to repair measures (TTR) for a work unit for all failure events (FE)."
Mean time between failures (MTBR)	"The mean operation time between failures is calculated as the mean of all time between failure measures (TBF) for a work unit for all failure instances (FE)."

When the whole formula for diagnosability is compiled, the quantities need to be similar. Since the proportion between inspected and produced will want to be as high as possible while APSR and MTTR / MTBF ratios should be as low as possible. Therefore, the fault identification metric needs to be converted to be as low as possible. To aim for a scale that ranges from 0-100%, an average is used when combining the different proportions in diagnosability. The full metric can be read in the Table 28 below:

Table 28 - Diagnosability

KPI Definition	
Content	
Name	Diagnosability
Description	Measures the ability to identify, isolate and correct problems through the data points: Inspected part (IP), produced quantity (PQ), actual compared to planned scrap ratio (APSR), mean time to repair (MTTR) and mean time between failures (MTBF)
Scope	Unit and process-unit
Formula	$Diagnosability = \frac{(1 - \frac{IP}{PQ}) + APSR + \frac{MTTR}{MTBF}}{3}$
Unit of measure	Ratio
Range	Min: 0, Max: Unlimited
Trend	The lower, the better
Context	
Timing	On-demand, periodically
Audience	Supervisor, Management
Production Methodology	Discrete, Batch, Continuous

6.1.1 Mapping of Data Points and Data Collection

An overview of the new created KPIs show that several elements were gathered from the ISO 22400 standard (2014). This has a big advantage in generalizability and commonality throughout the industry as the terms are widely used in the industry. An overview can be seen in

Table 29 and a full table can be seen in Appendix 4.

Table 29 - Mapping of Data Points

							Others													
		APT	AUBT	PQ	PSQ	SQ	MTTR	MTBF	IP	R	EL	# a	# p	SIC	EX	x(t)	µ(t)	v(t)	ε(t)	β(t)
New KPIs	Product (mix) flexibility										x	x	x							
	Production volume (demand) flexibility													x	x					
	Material handling flexibility															x	x	x	x	x
	Reconfigurtion quality	x	x							x										
	Diagnosability			x	x	x	x	x	x											

7 Conceptual Decision Support Tool

In this chapter a conceptual decision support model will be created from three main perspectives identified in the academia. Each perspective will be described and how different theories within each perspective help to form the conceptual model.

The conceptual model consists of three different decision criteria of manufacturing system performance, cost, and risk. The reason for a three pronged approach is that a sole focus on cost fails to account for improved customer satisfaction, capacity changes, functionality degree, and reconfiguration time and cost (Abdi & Labib, 2004; Abdel-Kader, 1999). Thus, to get an formula that will act as target function in the optimization program, it can be assumed the change of cost, risk and performance could act as a foundation, giving the following Equation 8:

Equation 8 - Optimization Formula for Investment Decisions

$$MIN = \Delta\%Cost + \Delta\%Risk - \Delta\%Performance$$

Where the percentages are calculated between the current state compared to during the design phase of the decisions support model, it has been adjusted and integrated with the process of early equipment management (EEM) (McCarthy, 2017). The model fits within the first step 'design and performance management' where the department's request monetary values from the management (McCarthy, 2017). The foundation of the financial evaluation is found in activity-based accounting where the activity level affects the outcome of the associated costs. An example involves that cost of set-ups increases if more set-ups are being made. In combination of life cycle cost analysis, which is supported in the early equipment management process, it is possible to evaluate the machines based on their lifetime costs for different activity levels and future scenarios.

MacStravic & Bucher's (1992) software investment process has acted as the basis for the components and workflow of the decision model, however, some modifications have been changed to fit with different scenario simulations. The newly developed process can be seen in Table 30. The relationship between program components within the conceptual decision support tool is illustrated in Figure 6.

Table 30 – Conceptual Decision Support User Workflow Process

1. Collecting data from the manufacturing system (Input)
2. Compute the current state
3. A subjective judgment of relative importance of criteria and constraints (Priorities)
4. Identifications of investment alternatives (proposals)
5. Computation and judgment with respect of uncertainty simulation (scenario simulation)
6. Summarization of the three factors by investment alternatives (estimating future state)
7. Combine annual cost benefits alternatives with system performance and risk parameters (decision support model)

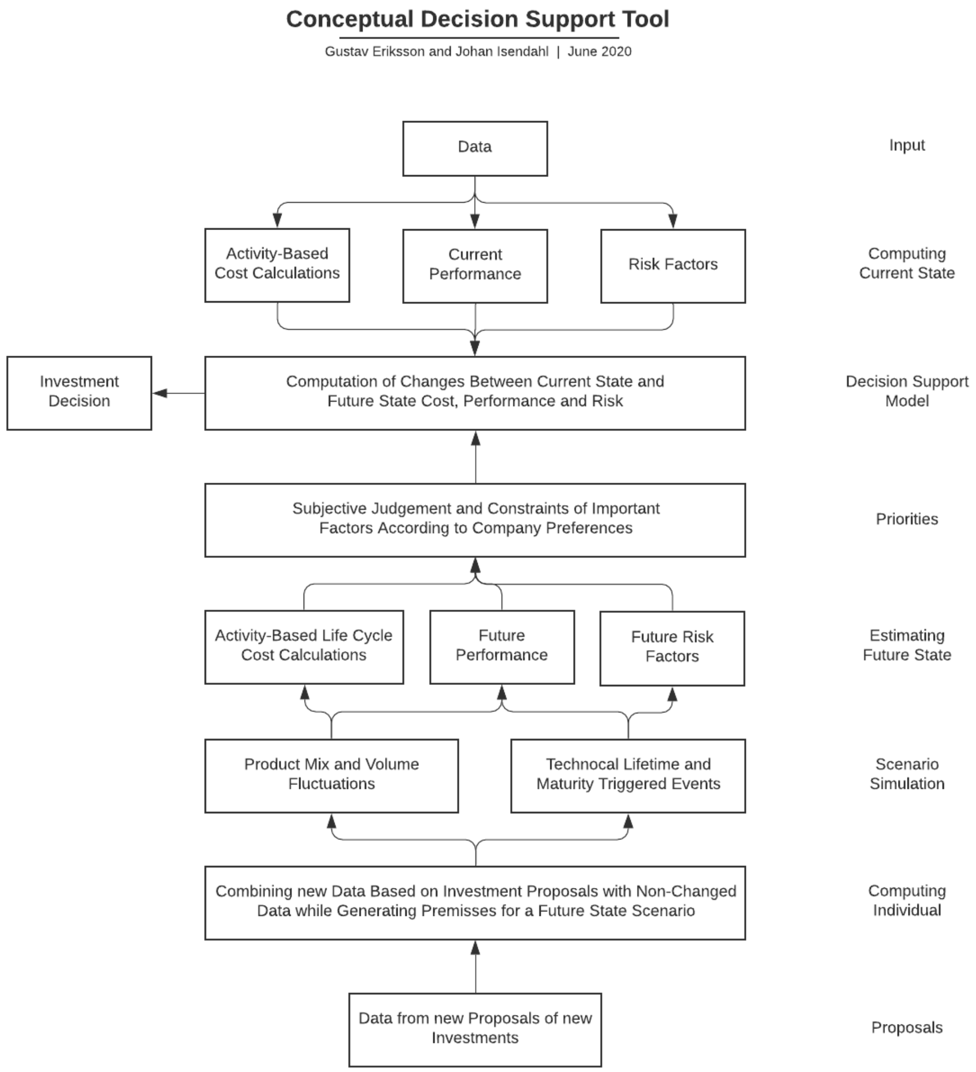

Figure 6 - Conceptual Decision Support Tool

7.1 Collecting Data and Computation of Current System Performance

In this phase, previously developed key performance indicators are used to evaluate the current system performance. In order to calculate these, it is necessary that the data from the data points have been collected in order to have a complete review of the parameters. The metrics are compiled below in, and the formulas are found in the report, and its data points can be read in Appendix 4 and the hierarchical level to be collected in Appendix 3 and Appendix 4.

Table 31 – Performance Parameters

Parameters
• Allocation efficiency
• Availability
• Mean operating time between failures
• Quality ratio
• Throughput rate
• Utilization efficiency
• Manufacturing lead time
• Process capacity limits
• Set-up time
• Ramp-up time
• Reconfiguration time
• Product (mix) flexibility
• Production volume (demand) flexibility
• Material handling flexibility
• Reconfiguration quality
• Diagnosability

7.2 A Subjective Judgment of Relative Importance

For companies to be able to adapt the model to their business and due to lack of research of weight, different relative importance aspects need to be considered. A way to address this involves using fuzzy numbers (Rashidi-Bajgan, et al., 2010; Abdel-Kader, 1999). Not only can the target function be valued differently, the metrics should also be able to assume different weights and have a limitation for the model to be able to provide reliable solutions.

7.3 Identifications of Investment Alternatives

When an improvement has been identified, the operator or production engineer need to identify all necessary data as seen in Table 31. When all data is gathered it needs to be put into the datasheet in the model. After the data has been inserted the model will calculate and present the best project or investment depending on what data has been inserted and what criterions that has been decided. The data that is presented will help the production engineer to decide what projects that should go to the investment committee in order to be approved. So, the model should only help the production engineer to choose those project that will go to the investment committee and not interrupted the process of approval.

7.4 Computation and Judgment with Respect of Uncertainty Simulation

It is possible to measure market risks by doing Monte Carlo simulations where you try to recreate historical patterns through probability theory and then try to predict the future (Renna, 2017). However, market risk has historically been measured in volatility by means of the standard deviation of, for example, customer demand for products. Thus, it should be relevant to adjust the performance figure to be statistically substantiated, which is found in the ISO-standard and should therefor follow the framework for the same. The problem with such an approach means that the metric does not become a performance indicator that describes companies' ability to deal with market risks. But since there is already a key performance indicator that is intended to describe this capacity (production volume flexibility), the indicator is transformed from the intended use area to become a data point that influences the investment method.

Equation 9 - Market Risk

$$Market\ risk\ = \frac{\sigma_{Demand}}{\mu_{Demand}}$$

Market risk relates to the fluctuations that occur in the market in volume and mix. The model assumes that there is an expected average sale with standard deviations over a forecasted period with accordingly expected product mix. The different production volumes and the number of products produced and batch sizes on a line should be considered when lifecycle costs for set-up, ramp-ups and reconfiguration occur. In the following Table 32 – Example of Mix and Volume FluctuationsTable 32 an example over mix and volume fluctuations can be seen. Depending on number of products and volume, an assumption can be made that activities related to changeovers and reconfigurations triggers extra cost based on different future scenarios.

Table 32 – Example of Mix and Volume Fluctuations

	Expected Demand									
	year 1		year 2		year 3		…		year n	
	Mean	Std	Mean	Std	Mean	Std	Mean	Std	Mean	Std
P0001	5	2	2	1						
P0002	3	1	4	2	2	2				
P0003			3	3	4	1				
P0004					5	1				
P0005					3	2				
Max Capacity	8		8		13		X_{MAX}		X_{MAX}	

Technological risk can be measured by using machine readiness level (MRL) in relation to the required level where it could be linked to a predetermined percentage where older manufacturing equipment has the risk of becoming obsolete. Suppliers ability to deliver spare parts should also be investigated in technological risk according to interview. Mixing data points with different numbers and scales makes it difficult to land in a percentage, so fuzzy set numbers should be adapted in such scenario to relative percentages set. General technology risk could be defined as a performance measurement as following Equation 10:

Equation 10 - Technology Risk

$$Technology\ risk\ = \frac{(MRL\ +\ fuzzy\ set\ lifetime\ +\ supplier\ ability)}{3}$$

The model has chosen a stochastic approach that simulates different events and their impact on the life cycle cost. One way of conducting another risk event is the technology risk and it compares the relationship between today's machine readiness level and required level for the investment period being evaluated. But could also include supplier risk and lifespan calculations. By conducting several subsequent Monte Carlo simulations, it is possible to extract an expected mean cost for MRL changes. Thus, the technical risk is assessed by different values that a machine either fails to meet future products, fails to fulfill its lifespan due to insufficient manufacturing method which result in a new machine acquisition. In the following Table 33, the cells readiness is evaluated in relation to the products expected to be produced.

Table 33 – Example of MRL Requirement Evaluation

	MRL Requirement Evaluation									
Cell	year 0	year 1	year 2	year 3	year 4	year 5	year 6	year 7	year…	year n
1	9	9	9	7	7	7	7	6	…	6
2	9	9	9	9	9	9	9	9	…	9
3	8	8	8	8	9	9	9	9	…	9
4	9	9	9	9	9	9	8	8	…	8
5	9	9	9	9	9	4	4	4	..	4

In the table below, different percentages can be assumed where the simulation triggers different events in relation to risk. The risk may be assessed by the production staff and can thus be evaluated based on suitability. Through the simulation, a value between 0-1 can be generated and generate different events, linked to different costs. ‘No event’ result in no extra charge, ‘modify’ results in a relative smaller fee and ‘new acquisition’ triggers a larger investment. The triggered events are converted into costs and hence be summed up to the lifecycle cost analysis and an example of data points can be seen in Table 34.

Table 34 – Example of MRL Risk Trigger Events

MRL Definition		Risks		
		No event	Modify	New Acquisition
1	Basic manufacturing implications identified	0%	0%	100%
2	Manufacturing concepts identified	0%	0%	100%
3	Manufacturing proof of concept developed	0%	5%	95%
4	Laboratory manufacturing process demonstration	6%	19%	75%
5	Manufacturing process development	10%	35%	55%
6	Critical manufacturing processes prototyped	18%	47%	35%
7	Prototype manufacturing system	32%	53%	15%
8	Manufacturing processes maturity demonstration	56%	44%	0%
9	Manufacturing processes proven	100%	0%	0%

Organize risk aims to create a risk evaluation of the management and system construction processes and its ability to meet the set requirements. (Xiaowen, et al., 2009). When you perform reconfigurations and changes, everything does not go perfectly. There is a risk in making these changes, which is called organizing risk. The reliability of the manufacturing line is calculated using *Equation 2* and Equation 3.

If a reconfiguration does not go as planned, then extra costs will be incurred that affect the line's lifecycle cost and thus non-customizable machines are considered at greater risk of creating unforeseen costs. In a stochastic analytical method, this can be done by using a normally distributed cost base to simulate its effects.

7.5 Summarization of Lifecycle Cost by Investment Alternatives

This part aims to summarize the life cycle cost based on various investment decisions in order to make a comparison based on previous simulations. Cost calculations can be visualized over time and based on time intervals for certain investment alternatives; it is possible to calculate the life cycle cost. The cost calculations and estimates may differ between industries, but the companies should have the opportunity to calculate the different structures based on their activity-based accounting principles. Hence, this process aims to give the user the understanding of how the number of adjustments in production changes over years, the lifecycle cost differs accordingly. The Table 35 illustrates a brief illustration of a lifecycle cost analysis summary for an investment alternative.

Table 35 – Example of Lifecycle Cost by Investment Alternative

	year 0	year 1	year 2	…	year n	Σ
Fixed cost	50	50	50			
Variable cost	10	12	13			
- Set-up cost	3	4	5			
- Ramp-up cost	2	2	2			
- Reconfig. Cost	3	3	4			
- Other	2	2	2			

7.6 Combine Annual Cost Benefits Alternatives with System Performance and Risk Parameters

The final step involves the calculation of the various parameters. Economical factor, non-financial factors and risk that can be weighted differently depending on preferences. The model summarizes six different calculations such as current cost, future cost, current risk, future risk, current system performance and future system performance. The percentage difference that arises between the equals is used in the target function to combine to the same base as the different factors have different quantities (costs and metrics).

8 Discussion and Conclusions

This chapter presents a discussion on how the method and analysis has been carried out and what problems and obstacles that has occurred along the way. It ends with a conclusions and future research.

8.1 Discussion of Method

Due to external factors, the focal company closed the factories during the period where the case study should be conducted. The result ended in that a very small portion of information could be gathered from the focal company. The information that was gathered was analyzed to the extent it could be and the authors tried to use the information as a guideline for insights in the study. As the focal company had external problems that made them pull out of the project, the data that were supposed to be gathered from the focal company were replaced with ISO standards in order to increase the generalizability and applicability.

The approach of the studied phenomenon was of a qualitative approach and was chosen due to the complexity and maturity of the area. The problem was of a characteristic that the authors interpreted could not be investigated through any quantitative method but rather needed an in-depth investigation. The majority of qualitative studies struggle with generalizability bias as described by Williamson (2002) and to co-op with the low generalizability and bias, standardized models were used. In the 'Method and Implementation' section, it can be seen that chapters 2.2, 2.3.2 and 2.4 use standardized models to define 'literature search', 'creation of KPIs' and 'analysis' of the report that otherwise would have lacked support in academia. The use of the standardized models helped to increase transferability as well as increasing conformability. Through increasing conformability or biases, it also reduced the subjectively that otherwise is a problem for influencing the qualitative study (Paul, et al., 2019).

The aim was to conduct a single case study at the focal company with methods as interviews, document study and a questionnaire. Each method had the purpose to fulfill the requirement for method triangulation and support the credibility, transferability, dependability, and conformability. The initial interviews were conducted to get an overview of the project and were carried out with people chosen in the appropriate area of the focal company. As the focal company needed to pause the project due to external factors all interviews that were planned could not be fulfilled, which left the authors with too little information. The remaining interviews were aimed to understand the investment process and to see what KPIs were used and that could be mapped to the chosen model. The document study was carried out to understand the processes and different templates at the focal company that is used during the investment process. The templates and documents received were gathered from production engineer 1 and a controller. This gave the authors the possibility to get opinions from two perspectives where the controller monitors the process and documents that need to be filled in while the production engineer is the one using them on a regular base. Also, here several more documents were meant to be received and the ones received cannot be shown due to secrecy. The questionnaire was meant to be sent out to verify the information gathered during the interviews. It was supposed to be sent out to the departments of the involved people. This increases the generalizability within the focal company and strengthen the subjectively. Through not being able to conduct the survey the ability to verify information decrease the transferability within the focal company and other similar companies.

The literature study was conducted to gain knowledge within the chosen area as the authors lacked in-depth knowledge. Even though an initial scan of the area was made before the actual search, the authors felt the need for making several searches to cover the whole field. This may be due to the lack of experience within the area of the topic. Even though several searches were made the risk of missing important theories and knowledge due to lack of knowledge needs to be taken into consideration. Two methods that are well known and used to counteract or reduce missing information in a literature search is snowballing and bibliography search. As the focal company paused the project the aim of the study was needed to be adjusted to meet the new challenges, hence changing the aim of the study. This created the need to make a second literature search on topics discovered during the interviews and compliment KPIs that were supposed to be gathered from the focal company. The ISO – standard was chosen for the mapping of data points instead of gathering them from the focal company.

During the analysis, several models were evaluated before the final one was chosen. Bergström & Jödicke’s (2019) model was first evaluated but was disclosed due to the abstract level it contained. The initial thought was to try and map their definition of enablers towards performance measurements but as the enablers are formulated for both qualitative and quantitative answers it made it hard to grasp in the context of performance measurements. Before the model where discarded several attempts to convert both qualitative and quantitative answers to fit and match better with the performance measurements were made. The second model investigated was Rösiö, et al., (2019) as it had a strong foundation in the creation of the model. Although it had a good mix of requirements related to performance measurements, it still had some abstract aspects that made it hard to be used to the full extent. This from the perspective that all elements should be covered and as the conversion in both Bergström & Jödicke (2019) and Rösiö, et al., (2019) were to complex another model were needed to be chosen. The final choice fell on Xiaowen (2009) as a part of the analysis was to understand what impact a manufacturing system wants to achieve and how an investment model could benefit from understanding that viewpoint. The common thread that were seen, was that investment models had troubles comparing manufacturing requirements between RMS vs DMS and FMS. This created a complexity that made RMS non beneficial since problems as uncertainty, effect on manufacturing system and long-term view existed.

Xiaowen (2009) addressed the complexity and to co-op with the uncertainty the relation towards manufacturing requirements and how it could be handled through measuring several strategies or KPIs within those strategies.

As the model was chosen the analysis method was applicated which helped to enrich the understanding of the model chosen and the literature that had been conducted. Through using a method, it helped to increase the replicability and thus take away the subjectively and the author's opinions.

After the focal company left the project a different approach was taken which lowered the applicability of the project and put another dimension to the time constraint as the plan was needed to be readjusted. Also, the complexity of carrying out the analysis delayed the project and created a lot of extra work. Due to this, the last research questions got cannibalized and the time for putting an investment model together decreased and became only a concept.

The study has taken a system perspective as the benefits of configurable solutions are perceived to be within the system's effects. Thus, there was an approach that could be more machine-oriented that could generate other analysis results and conclusions. Thus, there are opportunities to take a different research approach but there is the risk of optimizing machine investment but sub-optimizing the system effects.

8.2 Discussion of Findings

The purpose of this study was to investigate if it is possible to extend current assessment models and connect them to performance measurements. This to investigate if it is possible to evaluate the reconfigurability in the current manufacturing system without using reconfigurable characteristics. As the focal company paused their internal project during the case study period the findings section is very limited and contains only abstract information.

However, the findings that were succeeded to be gathered, contained a lot of information about the general process they use when investing in new equipment and how they can counteract the uncertainty in technology maturity in the future. As the information gathered contained processes that was not developed by the focal company an extra literature review was conducted where information could be complimented. This helped to increase the understanding of how the focal company worked during investments.

8.3 Discussion of Analysis

Research question 1: How can standardized key performance indicators be used to display the current and expected performance of a reconfigurable manufacturing system?

Through the process, different perspectives have helped to answer the first question. Since reconfigurable manufacturing systems have their main strengths in systems perspective, we suggest that you measure the overall performance of the manufacturing system when considering investment. According to this report, maximizing reconfigurability is considered a disadvantage as the industry does not want to over-invest in unused capabilities and build a completely modular system when only a few stations need reconfigurability. Thus, the report was based on manufacturing requirements such as short lead times, more variants, low and fluctuated volumes at a low cost. This was used as criteria when scanning performance metrics. The result of the analysis showed that there were six metrics that could be compared to standard 22400. These were allocation efficiency, availability, mean operating time between failures, quality ratio, throughput rate and utilization efficiency. With small funds it was possible to create new standardized measurement figures using the existing model. These were lead time, process capacity limits, set-up time, ramp-up time, and reconfiguration time.

> *Research question 2: How can reconfigurable system characteristics support the development of new key performance indicators where the academia lacks bearing?*

During the performance metrics development, there were five grouped metrics that did not have a given definition or design. In this step, an evaluation and analysis of available formulas that could be applied by the core characteristics were made. By linking the characteristics to the different definitions, new ones could be developed, and old ones strengthened. Reconfiguration quality was developed and standardized through ISO 22400 concepts. Diagnosability was defined according to its ability to detect, detect, and correct problems that arose. The flexibility formulas (product, production, and material handling) were chosen because they had aligned purposes with the characteristics.

> *Research question 3: How can a conceptual decision support tool be structured to facilitate stepwise investment decisions with associated key performance indicators?*

In investment decisions, a three-pronged approach was adopted which analyzed the manufacturing system based on three aspects. activity-based lifecycle cost, key performance indicators and risk. Through a refined investment process, a seven-step model (Table 30) was proposed that proposes how the decision support tool should be used and Figure 6showed how the decision paths are structured.

Given the weakened cooperation with the focal during the study, it remained difficult to anchor the industry beneficial part of the degree project. In any case, analyzing the theory based on the ISO standard gave a form of connection and reliability to the analysis part. On this topic, the discussion always recurs on whether relevance or generalizability should be a priority. The purpose of the analysis part was to consider and weight these factors and draw conclusions that were both generalizable and relevant. However, this is no simple task and it can be argued that the analysis has the problem of either/or, in its phase of defining key performance indicators

The study was intended to have a stronger connection to the characteristics initially, but existing assessment models in the academy were mainly based on quantitative fuzzy numbers, qualitative or methods which were not considered to correlate with performance in relation to manufacturing requirements, which was the initial drivers for the implementation of reconfigurable manufacturing systems. Manufacturing requirements are thus designed to satisfy the customer demand where reconfigurable manufacturing systems are a method of achieving this. Thus, it is more sensible to adapt key performance indicators to the goals and not how good you are at being reconfigurable.

Therefore, the authors consider that RMS should be considered as a framework for achieving manufacturing requirements and making investment proposals, but that decisions must be made according to the customer requirements that the organization is faced with. The relationship with performance metrics to the characteristics is not relevant unless one considers causality and correlations. For example, a high proportion of modularity would be feasible from a reconfigure perspective, but the system may not need to be modular in all cells because flexibility is only needed in certain steps and would lead to wasteful investment from an economic perspective. The timing, that is, the right investment at the right time, should have room for incremental investment models when it comes to decision support tools.

The solution is based on subjective weighting, which has both strengths and weaknesses. The strengths are based on the fact that a company has the opportunity to control their solutions based on their preferences, but this could also mean that the user of the model makes the wrong priority which would generate incorrect investment alternatives and would reduce the attraction to the tool. When talking about the convenience of reconfiguration, there may be underlying aspects and achievements that could be addressed in a KPI. A key performance indicator should not be too specific, but rather an in-depth analysis in different areas, and it is conceivable that you may need to break the concepts down further. Reconfiguration quality, for example, consists of different criteria such as ‘convenience of use’ that could be divided into different areas such as the time required to do the configuration, the number of steps in the process which should mean better performance if there are fewer steps. Another aspect that relates to peoples’ behavior could be what skill is required, the ergonomic aspect that prevents a person from being physically affected by the construction, the efficiency, the tolerance of mistakes and the need for specific tools and/or devices. As a result of there being poor academic grounds in these various aspects, it was difficult to justify an implementation of such metrics, but it could be an area to investigate in the future.

There is a problem when it comes to the ISO standard and that is when talking about different time units. There are either planned or real times. These are used mixed in the analysis which can create problems when it comes to comparisons. The idea, however, is to review actual outcomes with projected outcomes. This should explain whether there is order and control over the manufacturing system.

One strength of the report is that it has many similarities and utilization rates of the ISO standard, such as data points. This helps companies in the industry compare and evaluate each other. However, there may be an influence from the industry you operate in and for this reason the report has tried not to use too many ratios in the use of setup time, ramp-up time and reconfiguration time, although it may be considered relevant. For example, if a comparison is made between changeover time and lead time, for example, some industries would find it difficult to compare with each other.

When it comes to RMS, the research is limited in the subject area of the key performance indicator and there are opportunities for a better framework based around flexibility. In the project scope, however, there were not many articles in existence that had concrete and relevant system-level KPIs.

When carrying out a study like this, different aspect needs to be taken into consideration. For example, social factors need to be carefully evaluated to minimize the impact of the change for the employees. As the model changes the decision route from a knowledge-based decision to a rule-based decision, employees can feel disconnected and feel a lack of transparency in the model. This can also create demotivation as the responsibility is put on the model and not the knowledge-based person as before. Along with the model, the need to really understand the tool and company priorities increases which could enhance the employee loyalty as they get more involved in the company.

The tool helps to make long-term decisions about machine procurement and tools that enable companies to minimize the wear-and-tear mentality where modular parts can be shared within the machinery park. The ecological imprint can thus be assumed to be smaller and the model's view of life-cycle costs creates opportunities to take energy consumption, landfill and emission costs into account. Thus, there is the possibility of obtaining environmental benefits when implementing the decision tool, however, the model requires computational capacity but may be considered negligible in comparison.

8.4 Conclusions

The current studies in academia addresses the reconfigurable manufacturing system and are mainly based on quantitative fuzzy numbers or qualitative methods based on interpretations. The report proves that the key performance indicators used in the reconfigurable setting can, to some extent be standardized but to cover all areas of system capabilities, productivity, flexibility, and quality, are new indicators that need to be developed. By extracting information about the key aspects within the characteristics, new key performance can be used to address the gap within the academia.

To create a successful decision support model that facilitates investment decisions, it must be made by the strategical goal of the manufacturing system based on the manufacturing requirements. Since the reconfigurability manufacturing system strategy is based on the same premises, the concept can be seen and acted on as a conversion tool to achieve the manufacturing requirements. Hence, developing key performance measurements solely for reconfigurability creates disruptive goals in terms of economic utility. Instead, a three-pronged approach is needed to validate the investment decision in terms of changes in system performance, cost, and uncertainty. System performance can be assessed with the above-mentioned performance measurement, cost is assessed with an activity-based costing system in relation to stochastic simulations of flexible volume, flexible product mixes, and occurring risk events.

8.5 Implications and Future Research

The study helps to understand which performance-based metrics are relevant for evaluating manufacturing systems based on operational goals and manufacturing requirements. With the trends in a data-driven future with greater computational capacity, there is room for applications that can analyze different scenarios and at the same time collect a larger number of data points efficiently, therefore the study is seen as an atrium for what in today's situation is not considered viable to be standard in future equipment planning and acquisitions.

The report has set a direction for future research within the decision of incremental investments towards reconfigurability. First, a practical model needs to be developed to validate that the result generates reliable decisions and thus could also enhance the ability for further integration into the industry. Due to the overall result within the field, improvement and in-depth analysis of mathematical formulas could be required within the subject area of stochastic probabilities of reconfiguration and risk activities. A study is needed to investigate how to increase the perceptions and understanding of today's reconfiguration assessment models and key performance indicators within businesses. For the decision model to be validated and to provide the optimal solution, the weighting between different factors also needs to be investigated. Flexibility measurements exist in academia, but further research is wanted to evaluate which is relevant for the reconfigurability manufacturing systems and thus can be used as performance measurements. Another aspect involves a standardized cost calculation model for RMS which could act as a basis for defining and measuring a custom activity-based costing system. Lastly, how can current definitions of the characteristics be adjusted to display the performance goals and how can these be better integrated with key performance indicators.

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10 Appendices

Appendix 1

Standardization Matrix for Reconfigurability KPIs

Appendix 2

ISO-Standard and Adjusted Key Performance Indicators

Appendix 3

Data points for Key Performance Indicators and Hierarchical Gathering Phase for Data Points

Appendix 4

Data Points for New Key Performance Indicators and Hierarchical Gathering Phase for Data Points

Appendix 1

	Availability	Actual to planned scrap ratio	Allocation efficiency	Allocation ratio	Comprehensive energy consumption	Corrective maintenance ratio	Critical machine capability index	Critical process capability index	Effectiveness	Equipment load ratio	First pass yield	Finished goods ratio	Fall off ratio	Integrated goods ratio	Inventory turns	Machine capability index	Mean operatiom time between failures	Mean time to faulure	Mean time to repair	Net equipment effectiveness index	Other loss ratio	Overall equipment effectiveness Index	ProdRAtion process ratio	Process capability index	ProdRAtion loss ratio	Quality ratio	Rework ratio	Scrap ratio	Storage and transporation loss ratio	Setup ratio	Techincal efficiency	Throughput rate	Utilization efficiency	Worker efficiency
System capabilities																																		
Process capacity limits										RA																								
Balancing			RA																															
Set-up time																														RA				
Ramp-up time																														RA				
Reconfiguration time																														RA				
Lead time																																RA		
Diagnostability																	NA																	
Mean time between failures																	DA																	
Productivity																																		
Production rate																																DA		
Equipment utilization																																	DA	
Availability	DA																																	
Flexibility																																		
Product (Mix) Flexibility																	NA																	
Production Volume (Demand) Flexibility																	NA																	
Material Handling Flexibility																	NA																	
Quality																																		
Reconfiguration quality																	NA																	
Product quality																										DA								
Risk																																		
Technology risk																	NA																	
Organize risk																	NA																	
Market risk																	NA																	

Appendix 2

Reconfigurability KPIs	ISO-standard	Definition
Availability	Availability	Availability is a ratio that shows the relation between the actual production time (APT) and the planned busy time (PBT) for a work unit.
Mean time between failures	Mean time between failures	The mean operation time between failures is calculated as the mean of all time between failure measures (TBF) for a work unit for all failure instances (FE).
Production rate	Throughput rate	Process performance in terms of produced quantity of an order (PQ) and the actual execution time of an order (AOET),
Equipment utilization	Utilization efficiency	The utilization efficiency is the ratio between the actual production time (APT) and the actual unit busy time (AUBT)
Product quality	Quality ratio	The quality ratio is the relationship between the good quantity (GQ) and the produced quantity (PQ),
Balancing	Allocation efficiency	Allocation efficiency is the ratio between the actual allocation time of a work unit expressed as the actual unit busy time (AUBT) and the planned time for allocating the work unit expressed as the planned unit busy time (PBT)

Reconfigurability KPIs	ISO-standard adjustments	New definition	Explanation
Process capacity limits	Process production capacity (Equipment production capacity)	Process production capacity is the maximum production quantity of a production process or cell.	Has similarities to equipment production capacity (EPC) and can thus be transformed into process production capacity where the lowest capacity in a flow is regarded as the limit according to the theory of constraints.
Set-up time	Planned Unit Set-up time (Planned unit set-up time)	The planned unit setup time shall be the planned time for the setup of a work unit for an order.	An underlying data point to the standard ‘set-up ratio’ is equivalent to the key performance indicators described in previous chapter
Ramp-up time	Planned Unit Ramp-up time (Planned unit set-up time)	The planned unit ramp-up time shall be the planned time for the ramp-up of a work unit for an order,	Builds on the 'planned unit set-up time' data point used in set-up ratio but has been adjusted set-up time to ramp-up time
Reconfiguration time	Planned Unit Reconfiguration time (Planned unit set-up time)	The planned unit reconfiguration time shall be the planned time for the reconfiguration of a work unit for a new process.	Similar changes as for the ‘planned unit ramp up time’ where definitions from reconfiguration time have been applied to the datapoint
Lead time	Planned Order Execution Time	The planned order execution time shall be the planned time for executing an order.	Planned order execution time sums up all planned time for executing an order

Appendix 3. Data points for Key Performance Indicators and Hierarchical Gathering Phase for Data Points

Appendix 3

		ISO Standard																		
		ADET	AOET	APAT	APT	APWT	AUBT	AUPT	AUST	PBT	EPC	PRI	E	GP	GQ	PQ	PSQ	RQ	SQ	IGQ
ISO-Standards	Allocation efficiency						X			X										
	Availability				X					X										
	Mean operating time between failures																			
	Quality ratio														X	X				
	Throughput rate		X													X				
	Utilization efficiency				X		X													
Adjustment	Lead time																			
	Process capacity limits																			
	Set-up time																			
	Ramp-up time																			
	Reconfiguration time																			

		ISO Standard																Others		
		IP	Cm	OL	PL	STL	PMT	FE	TBF	TTF	TTR	CMT	LSL	USL	Deviat,	PUST	σ	PCL	PRUT	PRFT
ISO-Standards	Allocation efficiency																			
	Availability																			
	Mean operating time between failures							X	X											
	Quality ratio																			
	Throughput rate																			
	Utilization efficiency																			
Adjustment	Lead time																			
	Process capacity limits																	X		
	Set-up time															X				
	Ramp-up time																		X	
	Reconfiguration time																			X

AOET	actual order execution tim	TBF	operating time between failure
APT	actual production time	PUST	planned set-up time
AUBT	actual unit busy time	σ:	standard deviation
PBT	planned busy time	PCL	process capacity limit
GQ	good quantity	PRUT	planed ramp-up time
PQ	produced quantity	PRFT	planned reconfiguration time
FE	failure event		

Appendix 3. Data points for Key Performance Indicators and Hierarchical Gathering Phase for Data Points

		Hierarchical Gathering Phase			
		Factory	Line	Cell	Machine
Data points for Key Performance Indicators	Actual Order Execution Time		X		
	Actual Production Time		X		
	Actual Unit Busy Time			X	
	Planned Busy Time				X
	Equipment Production Capacity				X
	Good Quantity		X		
	Produced Quantity		X		
	Failure Event		X		
	Operating Time Between Failure			X	
	Planned Unit Set-Up Time			X	
	Process Capacity Limit				X
	Planed Ramp-Up Time			X	
	Planned Reconfiguration Time			X	

Appendix 4

ISO Standard

New KPIs	ADET	AOET	APAT	APT	APWT	AUBT	AUPT	AUST	PBT	EPC	PRI	E	GP	GQ	PQ	PSQ	RQ	SQ	IGQ	IP	Cm	OL	PL	STL	PMT	FE	TBF	TTF	TTR	CMT	LSL	USL	Deviat,	PUST	σ
Product (mix) flexibility																		N/A																	
Production volume (demand) flexibilit																		N/A																	
Material handling flexibility																		N/A																	
Reconfigurtion quality				x		x																													
Diagnosability															x	x		x																	

Others

New KPIs	MTTR	MTBF	IP	R	EL	# actual	# planned	SIC	EX	x(t)	μ(t)	v(t)	(t)	β(t)
Product (mix) flexibility					x	x	x							
Production volume (demand) flexibilit								x	x					
Material handling flexibility										x	x	x	x	x
Reconfigurtion quality				x										
Diagnosability	x	x	x											

APT	actual production time	# Actual	# of product families that can be used
AUBT	actual unit busy time	# Planned	Total # of product families that is planned during the economical lifetime
PQ	produced quantity	SIC	Smalles incremental capacity
PSQ	planned scrap quantity	EC	Existing capacity
SQ	scrap quantity,	μ x(t)	is the number of material handling components at time t
MTTR	Mean time to repair	ε(t)	is the maximum unit load quantity factor based on capacity of the equipment at time t
MTBF	Mean time between failure	v(t)	is the equipment speed based on the normal operating speed of the equipment at time t
IP	Inspected part	β (t)	the equipment loaded travel factor at time t
R	Reliability	(t)	is the relative rerouting cost indicating ability of equipment reconfiguration time t.
EL	Economical lifetime		

Appendix 4 – Data Points for New Key Performance Indicators and Hierarchical Gathering Phase for Data Points

		Hierarchical Gathering Phase			
		Factory	Line	Cell	Machine
Data points for Key Performance Indicators	Actual production time		X		
	Actual unit busy time			X	
	Produced quantity		X		
	Planned scrap quantity			X	
	Scrap quantity			X	
	Mean time to repair			X	
	Mean time between failure			X	
	Inspected part			X	
	Reliability			X	
	Economical lifetime				X
	# of product families that can be used				X
	Total # of product families that is planned during the economical lifetime				X
	Smallest incremental capacity				X
	Existing capacity				X
	The number of material handling components at time t				X
	The maximum unit load quantity factor based on capacity of the equipment at time t				X
	The equipment speed based on the normal operating speed of the equipment at time t				X
	The equipment loaded travel factor at time t				X
	The relative rerouting cost indicating ability of equipment reconfiguration time t.				X