



CHALMERS
UNIVERSITY OF TECHNOLOGY



Exploration of Different Production Flow Setups in Manufacturing Facilities

Evaluating Production Scenarios for SKF's Roller Production

Master's thesis in Supply Chain Management

JOEL PETTERSSON
MAX LORENTZON

DEPARTMENT OF TECHNOLOGY MANAGEMENT AND ECONOMICS
Division of Supply and Operations Management

CHALMERS UNIVERSITY OF TECHNOLOGY
Gothenburg, Sweden 2024
www.chalmers.se

Exploration of Different Production Flow Setups in Manufacturing Facilities

Evaluating Production Scenarios for SKF's Roller Production

JOEL PETTERSSON
MAX LORENTZON

Department of Technology Management and Economics
Division of Supply and Operations Management
CHALMERS UNIVERSITY OF TECHNOLOGY
Gothenburg, Sweden 2024

Exploration of Different Production Flow Setups in Manufacturing Facilities
Evaluating Production Scenarios for SKF's Roller Production
JOEL PETTERSSON
MAX LORENTZON

© Joel Pettersson, 2024
© Max Lorentzon, 2024.

Supervisor: Per Medbo, Technology Management and Economics
Examiner: Per Medbo, Technology Management and Economics

Department of Technology Management and Economics
Chalmers University of Technology
SE-412 96 Gothenburg
Sweden
Telephone + 46 (0)31-772 1000

Exploration of Different Production Flow Setups in Manufacturing Facilities Evaluating Production Scenarios for SKF's Roller Production

JOEL PETTERSSON
MAX LORENTZON

Department of Technology Management and Economics
Chalmers University of Technology

ABSTRACT

This thesis investigates the optimization of production systems at SKF, a global leader in the manufacturing of bearings, focusing specifically on roller manufacturing in Gothenburg, Sweden. Given the rapid advancements in industrial manufacturing SKF seeks to increase the efficiency of their roller production. This study assesses two contrasting production scenarios, Simplified Flow and Flexible Flow, to determine which aligns best with SKF's strategic objectives and the inherent challenges of the production environment. The primary aim is to evaluate these systems against key performance indicators, ultimately aiding SKF in refining its production processes.

Research Questions (RQ):

1. *What does the current situation look like for roller manufacturing at SKF?*
This question seeks to describe the baseline operations and existing challenges within SKF's roller production. A VSM was conducted to answer RQ1.
2. *What problem areas can be identified connected to the current situation?*
This focuses on pinpointing specific issues that could be addressed by changes in the production system. RQ2 was answered by identifying problem areas derived from interviews, observations, and the VSM where 6 problem areas were identified.
3. *What are the main differences between the two proposed production scenarios and how do they manage the identified problem areas?*
This question compares the two production scenarios in detail, examining how each manages the identified problem areas. The Simplified Flow focuses on flow efficiency whilst Flexible Flow focuses on resource efficiency.
4. *Which of the two proposed production scenarios for SRB rollers is most suitable for SKF?*
The final question aims to conclude which production scenario best fits the strategic and operational goals of SKF. RQ4, by combining the results from an MCDA analysis and how the respective scenario manages the identified problems, resulted in a recommendation to implement, and move toward the Simplified Flow along with aspects taken from the Flexible Flow.

This research utilizes a mixed-method approach, incorporating both qualitative and quantitative data from interviews, observations, and internal documents. Through analysis framed by a literature review in production systems, this study contributes to the decision-making process at SKF and extends practical implications for the broader field of industrial manufacturing.

Keywords: Production systems, production layout, material flow, value-stream mapping, performance objectives, Key Performance Indicator (KPI), Multi-Criteria Decision Analysis (MCDA), Flow Efficiency, Resource Efficiency, Real Flexibility

ACKNOWLEDGMENTS

This master's thesis was written during the spring of 2024 as part of the supply chain management program at Chalmers University of Technology, in cooperation with SKF.

We would like to express our appreciation to everyone who contributed to this thesis, with special thanks to our supervisor, Per Medbo, for his expertise and guidance.

We are also deeply grateful to Jörg Schlager and Johanna Bengtsson at SKF for granting us the opportunity to conduct this thesis and for providing us with valuable assistance and direction. Additionally, we would like to extend our thanks to the interviewees and all operators who provided us with their time and support during observations and data collection.

Joel Petterson & Max Lorentzon
Gothenburg, 2024

Table of Contents

List of Figures	i
List of Tables.....	ii
1. Introduction	1
1.1 Industrial Manufacturing Market.....	1
1.2 SKF.....	3
1.2.1 SKFs Roller Manufacturing	3
1.3 Problem Definition	5
1.4 Purpose & Research Questions.....	8
1.5 Scope & Delimitations.....	9
2. Methodology	10
2.1 Research Approach.....	10
2.2 Research Strategy	10
2.3 Data Collection	11
2.3.1 Observations.....	11
2.3.2 Interviews	11
2.3.3 Literature Review	12
2.3.4 Current State Map	13
2.3.5 Multi-Criteria Decision Analysis (MCDA).....	14
2.4 Research Ethics.....	14
2.5 Project Process.....	15
3. Literature Review	16
3.1 Production System.....	16
3.1.1 Volume and Variety	16
3.1.2 Layout and Flow.....	17
3.1.3 Push versus Pull Systems	19
3.2 Manufacturing Planning and Control	20
3.2.1 Materials Planning Methods.....	21
3.3 Theory of Constraints	22
3.4 The Bull-Whip Effect	23
3.5 Flow- versus Resource Efficiency	24
3.6 Value Stream Mapping (VSM).....	26
3.6.1 Waste	27
3.6.2 Current State.....	28
3.6.3 Future State	29
3.7 Evaluation of Production Systems.....	29

3.7.1	Performance Objectives	30
3.7.2	MCDA.....	32
4.	Current Production System	33
4.1	Production Environment.....	33
4.1.1	Production Strategy	33
4.1.2	Distribution Network of SRB.....	34
4.1.3	Production Process of Rollers	36
4.2	Current State Map.....	38
4.2.1	Production Flow	42
4.2.2	Information Flow.....	45
4.3	Identified Problem Areas.....	45
4.3.1	Takt Time	45
4.3.2	Overproduction and Excess Inventory	46
4.3.3	Transport	47
4.3.4	Constraints.....	48
4.3.5	Personal Judgement Decisions	48
4.3.6	System Support	49
5.	Production Scenarios.....	50
5.1	Main Differences between Simplified Flow and Flexible Flow.....	50
5.1.1	Simplified Flow	50
5.1.2	Flexible Flow.....	51
5.2	Management of Identified Problem Areas in Respective Production Scenarios	53
5.2.1	Takt time	53
5.2.2	Overproduction and Excess Inventory	54
5.2.3	Transport	55
5.2.4	Constraints.....	56
5.2.5	Personal Judgement Decisions	57
5.2.6	System Support	58
5.3	MCDA	59
5.3.1	Input to MCDA	59
5.3.2	MCDA Result.....	64
5.4	Summary of Results.....	65
6.	Discussion	67
7.	Conclusion.....	71
7.1	Recommendations	71
7.2	Further Research.....	72
	References	73

Appendix A iv
Appendix B v
Appendix C vi

List of Figures

Figure 1 Components of an SRB (Internal Document).....	4
Figure 2 Simplified Flow Scenario	6
Figure 3 Flexible Flow Scenario	7
Figure 4 Seven Steps of the Project Process	15
Figure 5 The Product-Process Matrix (Slack et al., 2013)	17
Figure 6 Illustration of the Bull-Whip Effect (Preston, 2022)	23
Figure 7 Efficiency Matrix (Modig & Åhlström, 2012)	25
Figure 8 Steps Involved in VSM Analysis (Rother & Shook 2002).....	26
Figure 9 Sand-Cone Model Based on Slack and Lewis (2015) and Bellgran and Säfsten (2010)	31
Figure 10 Distribution Network of SRB	35
Figure 11 Production Process of Rollers.....	36
Figure 12 RRY4-5 Current State Map	40
Figure 13 DRQ2 Current State Map	41
Figure 14 KPI Rankings by The Interviewees	60
Figure 15 Graphs Showing Weighted Score on Each KPI.....	64
Figure 16 Combined Score of Current State, Simplified Flow, and Flexible Flow	65

List of Tables

Table 1 Summary of SKF Key Figures. (SKF, 2022; SKF, 2023)	3
Table 2 Description of Scenario KPIs	8
Table 3 Roles of the Eight Interviewees	12
Table 4 Explanation of Strategies Used to Counteract the Bull-Whip Effect (Lee et al., 1997)	24
Table 5 Eight Wastes (Eaton, 2013; Liker and Meier 2006)	27
Table 6 Eight VSM Questions (Rother & Shook, 2004).....	29
Table 7 Results from the Rankings	60
Table 8 Definition of Each KPI Level	61
Table 9 Final Result of MCDA	64

1. Introduction

The purpose of this chapter is to provide the reader with a brief introduction to the project's background, which will help to better understand its objectives and research questions. The chapter will touch on relevant topics before briefly presenting SKF and the company's current project related to the study area. Finally, the problem statement and research questions will be presented.

1.1 Industrial Manufacturing Market

In the dynamic and ever-evolving world of industrial manufacturing, companies are continually challenged to adapt and innovate to maintain their competitive edge. With customer requirements evolving rapidly, manufacturers face the challenge of decreasing production expenses, shortening product delivery timelines, and upholding consistent quality. To address these challenges, one strategy for manufacturers is to refine or advance their production systems to increase the operational effectiveness of their manufacturing activities (Bellgran & Säfsten, 2010; Choudhari et al., 2010; Koren & Shpitalni, 2010). Hill (2009) further emphasizes the necessity of a well-defined production strategy for effective management of the various challenges encountered by the production function of a company. This strategy enables a company to make operational and strategic decisions coherently that align with the corporate strategy and the competitive priorities of the organization.

SKF, which stands as a global leader in the manufacturing of various types of bearings, is reflecting these broader challenges and opportunities in the industry. With a significant presence across over 130 countries (SKF, 2023), the company's operations exemplify the complexities and demands of sustaining a leading position in today's competitive landscape. The company's factory in Gothenburg, specializing in the production of spherical roller bearings (SRBs), represents a small part of these challenges. Producing a wide range of bearings, from 180mm to 2.5 meters in diameter and a variation in weight between 5kg to 10,800kg, the facility's diverse output demands adaptability, efficiency, and precision—qualities that are critical for maintaining SKF's competitive edge and market leadership. Currently in the process of transforming its production strategy for the rollers, a crucial component in the SRB. This strategy is still not defined and decided upon, but two conceptualized production scenarios have been developed.

Slack and Lewis (2015) state that an organization's capabilities are integral to its strategy and essential for maintaining its sustainability over time. Flexibility, considered one of these capabilities, is closely linked to the production system (Bellgran & Säfsten, 2010). Flexibility is defined as the capability to efficiently adapt and/or modify production processes to meet the required changes. In the context of manufacturing, this often correlates with the capacity to handle fluctuations in output quantities or a diverse range of product variants within a specified volume. In addition, manufacturing systems could manage variations with flexibility, without causing any interruptions in the production process (Manu et al., 2018). However, the types of flexibility could be different depending on the context, and for each company, the necessity and importance of a specific type of flexibility will vary depending on the company (Bellgran & Säfsten, 2010).

SKF's consideration of the two different production scenarios exemplifies the practical challenges and strategic decisions involved in achieving such operational adaptability. The scenarios, aimed at either simplifying the production flow or introducing more flexibility through varied processing routes, illustrate the decisions companies must make to align their production systems with broader strategic objectives. This ambition not only highlights SKF's commitment to maintaining its competitive edge through operational excellence but also serves as a case study for the types of flexibility and strategic considerations emphasized by Bellgran & Säfsten (2010).

According to Bellgran and Säfsten (2010), evaluation is an important part of the development of a production system. However, it is implied that evaluation is often seen as a neglected activity by manufacturing companies. The reason for this is, more often than not, the lack of time and not knowing how to do it. In the context of evaluating alternative production systems, it is considered important first to evaluate the existing systems and after that compare the alternative systems against each other (Bellgran & Säfsten, 2010). Carefully evaluating the production systems is important since it affects the overall operational performance (Islam et al., 2022). The implications of this decision extend beyond immediate operational concerns, leading to broader aspects like material handling, safety stock management, and lot sizing – elements fundamental to the smooth functioning of manufacturing processes (Islam et al., 2022). The production system design has been emphasized for years to ensure performance (Johansson & Johansson, 2006), where Slack et al., (1995) say that the design affects quality, speed, dependability, flexibility, and cost. In addition, Bennett (1986) states:

“... while effective control is doubtless necessary, the way in which a production system is designed will enable or preclude the possibility of achieving the best results.”

In the case of SKF's strategic transformation of its roller production system, and in line with what this master thesis will investigate, an evaluation of the two production scenarios is of high importance, in assessing and shaping the future of manufacturing operations. It's not only about choosing between different levels of flexibility but also about understanding how these choices align with the company's production environment and the demands of a competitive market. This thesis thus becomes an illustration of the necessity for evaluation in the design and refinement of production systems, ensuring that the chosen strategy optimally supports the operational requirements to meet the needs of the market.

1.2 SKF

SKF stands as a well-known global company in the manufacturing sector, primarily focused on the production of various types of bearings. Established in 1907 by Sven Wingquist in Sweden, the company has expanded its operations to include 77 manufacturing facilities worldwide, employing over 40,000 individuals. It holds a significant presence in the global market, serving customers in more than 130 countries, and holds a leading position in several industries, including industrial distribution, heavy industries, and the railway sector. In the year 2023, SKF reported revenues of 103,881 million SEK and a net income of 6,777 million SEK. A summary of these financial figures, along with a comparison of the previous year, is provided in Table 1 for reference.

Table 1 Summary of SKF Key Figures. (SKF, 2022; SKF, 2023)

SKF	2022	2023
Employees	> 42 000 people	> 40 000 people
Revenues	96 933 MSEK	103 881 MSEK
Net income	4 855 MSEK	6 777 MSEK

The SKF corporate headquarters is located in Gothenburg, Sweden, employing approximately 1,000 individuals across the main office and production facilities within its area. Initially, the factory specialized exclusively in the production of ball bearings, a focus that has since shifted to solely manufacturing roller bearings. The Gothenburg facility boasts an annual output of approximately 1.2 million bearings, encompassing a diverse range of up to 8,200 different variants. This diverse range is segmented into three distinct manufacturing units: the R-, D-, and E-factories, each dedicated to producing specific assortments of products within separate buildings. The R-factory is tasked with the manufacturing of roller components essential for bearings, which are then distributed to the D- and E-factories for assembly into complete bearings (only larger bearings in the E-factory). Although all types of rollers for various bearings are manufactured in the R-factory, those designated for the SRB represent the highest volume of production.

1.2.1 SKFs Roller Manufacturing

As previously mentioned, the SKF factory in Gothenburg specializes in the production of roller bearings, with SRB representing the primary output, accounting for over 80% of the annual shipped tonnage¹. From a financial perspective, SRBs contribute to roughly 70% of the Gothenburg factory's total revenue.²

¹ (J. Schlager, personal communication, January 25, 2024)

² (D. Ortega, personal communication, February 19, 2024)

SRBs are distinguished by their high load-bearing capacity and their ability to compensate for some degree of misalignment, attributed to their design which accommodates both axial and radial loads. An SRB is composed of various components which are ultimately assembled to form the finished product. These components, as illustrated in Figure 1, include an inner ring, a guide ring, a cage to secure and hold the rollers in place, the rollers themselves, and an outer ring. For one bearing, the number of rollers included varies between 40-60 pcs. In the performance of the complete bearing, each component carries equal significance. However, from a financial perspective, the roller component accounts for approximately one-third of the bearing's total manufacturing cost. This financial impact elevates its importance, therefore being the reason why the production of this is still being made in-house.²



Figure 1 Components of an SRB (Internal Document)

The production of SRB necessitates the internal manufacturing of rollers, a process taking place in the R- and D- factories. These facilities maintain a diverse possible production of approximately 130 different roller dimensions.³ The production of the rollers follows a make-to-order (MTO) strategy since orders are being pulled from the system. However, due to various reasons, a finished goods location exists, thereby making some rollers have a make-to-stock (MTS) strategy. The process initiates with the procurement of raw materials, specifically bars, from external suppliers. Upon their arrival at the factory, they go through several process steps including cutting the bars into rollers and pressing them for appropriate dimensions, followed by a heat treatment operation, and finally, they go through the operations of grinding and honing before being sent for assembly into a finished bearing.²

The dimensions of rollers will vary depending on the size of the bearing that they will fit into, and the tolerance level of a roller is of different matter depending on the company policy and the quality wanted for the bearing.⁴ SKF stands out from its competitors when looking at quality, making this aspect of high importance to the company. This great effort to provide high quality to its customers affects the manufacturing of the rollers, making the accepted tolerance level very low and precise. This impacts the way the production system is set up and operated to be able to meet this high demand for quality.

² (D. Ortega, personal communication, February 19, 2024)
³ (J. Bengtsson, personal communication, January 30, 2024)
⁴ (D. Agnemar, personal communication, March 5, 2024)

1.3 Problem Definition

The market for the finished SRBs is perceived as relatively stable, evidenced by historical data and projected sales forecasts.⁴ Possessing a quarter of the global market share, mentioned in Astute Analytica (2023), and with an increase between 3-5 % during 2023 which is emphasized in SKF (2023), SKF currently stands as one of the biggest within its sector, with a strategic objective to maintain its leading position. To achieve this, SKF acknowledges the necessity of enhancing its internal processes, particularly within its manufacturing facilities. This emphasis on improvement is crucial as competitors are also committed to ongoing advancements in their operations, underscoring the competitive landscape in which SKF operates (Slack et al., 2013).

The factories tasked with manufacturing the roller component for the SRBs, the R- and D-factories, are in the middle of a transformative process. This process involves modifying the way that rollers are currently being planned and processed in the production system, by moving towards having either a higher or lower level of flexibility than today.

The production system itself comprises two distinct production flows, hereby referred to as RRY4-5 and DRQ2, where the initial letter of each production flow designation signifies the factory in which the flow is situated. One production flow consists of the same processing steps, starting with the first process of a bar that is being cut and pressed into a roller. The roller is then hardened in a heat treatment machine for the second process, and the final process is where the rollers are grinded and honed in one of the seven machine groups, referred to as RR07-13.

The production flow of RRY4-5 incorporates two parallel production lines at the beginning of the process. This setup is characterized by a less integrated flow among operations, relying on manual transportation between the different processes in the production flow. Initially, conveyor belts facilitate the movement between the cutting and pressing operations. After pressing, the rollers are manually transported to the heat treatment operation. Once hardened, the rollers require another manual transportation to reach the final stages of grinding and honing. Additionally, there is a storage area where the rollers can be temporarily held before proceeding to these final operations.

The production flow of DRQ2 features a conveyor belt that extends from the first process of cutting and honing up to and including the heat treatment process. Once hardened, the rollers are manually transported to the grinding and honing, also having the option for storage in between at the same location as for RRY4-5.

The final process including grinding and honing, which is located in the R-factory, is a shared process between RRY4-5 and DRQ2, meaning that the rollers are transported between the R- and D- factory. Due to this process being a shared process, it is more complicated from a planning- and material flow perspective.³

³ (J. Bengtsson, personal communication, January 30, 2024)

⁴ (D. Agnemar, personal communication, March 5, 2024)

In the context of this transformative process, the company has developed two conceptualized production scenarios where each of which offers a different degree of flexibility to the production system. One production scenario, Simplified Flow, is centered around simplicity in the sense that the material flow for rollers would pass through one production flow in one simple path always using the same resources of operations. The second production scenario, Flexible Flow, would instead be centered around a less simplistic system that offers flexibility where it is possible to distribute the rollers between the production flows through different resources of operations depending on each specific situation. Regarding the Flexible Flow, the word “flexibility” is therefore associated with the ability to process rollers in different production flows instead of just one specific flow every time.

Simplified flow, as seen in Figure 2, is built on the idea of having an easy-to-follow flow of material through the production system. Looking at the production flow of RRY4-5, one dimension span of rollers would always be taking the same route, starting with consistently being processed in e.g., RRY4 for cutting and pressing before entering the heat treatment. After heat treatment, the same rollers would always be processed in one of the grinding and honing processes, e.g., RR07, and never in any of the others. Another dimension span would consistently be processed in for example RRY5 and RR08 instead, and so on. The same philosophy goes for DRQ2, with the difference of only having one production line in the cutting and pressing process.

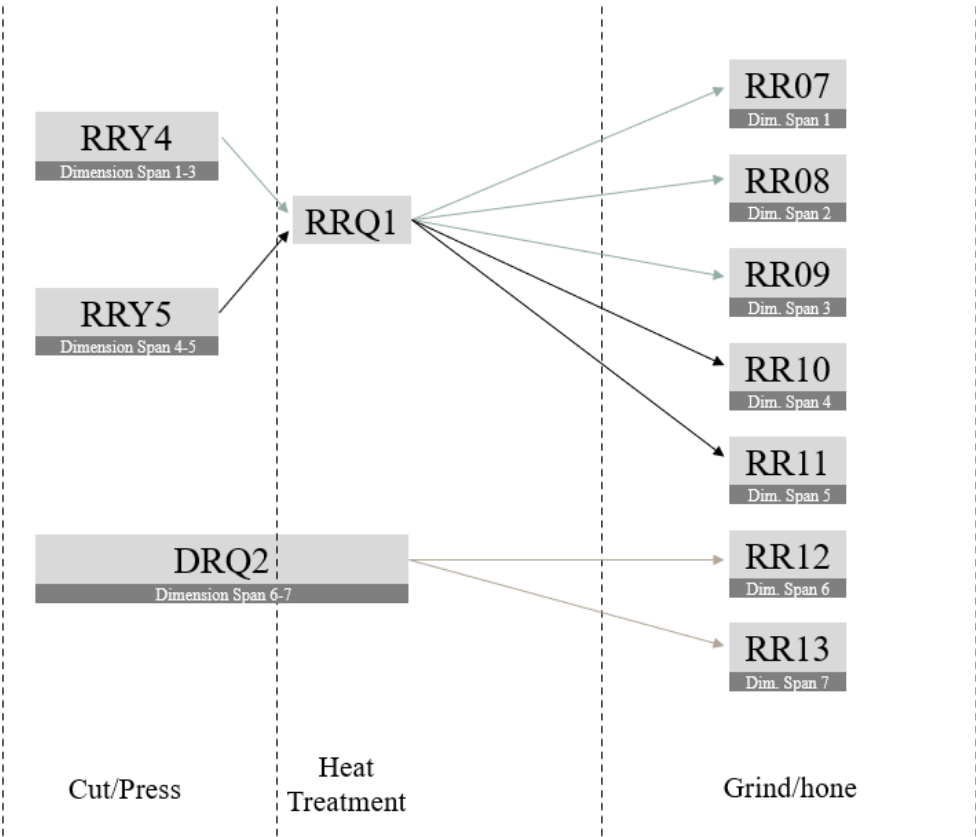


Figure 2 Simplified Flow Scenario

Flexible Flow, as seen in Figure 3, is instead built on the idea of a more flexible flow of material in the production system, having the opportunity to utilize more resources for the same dimensions of rollers. Instead of having a predetermined path for a specific dimension span of rollers, the rollers can be processed and take a route in whichever process is available at that specific time, making it possible to redirect them and move them between processes. Looking at the heat treatment operation, the rollers can be processed in the first available grinding and honing operation. A specific dimension of roller can one day be taking the route from RRY4 to RR07, and another day from RRY5 to RR13, all depending on the first available process. The same philosophy is also here applied to DRQ2.

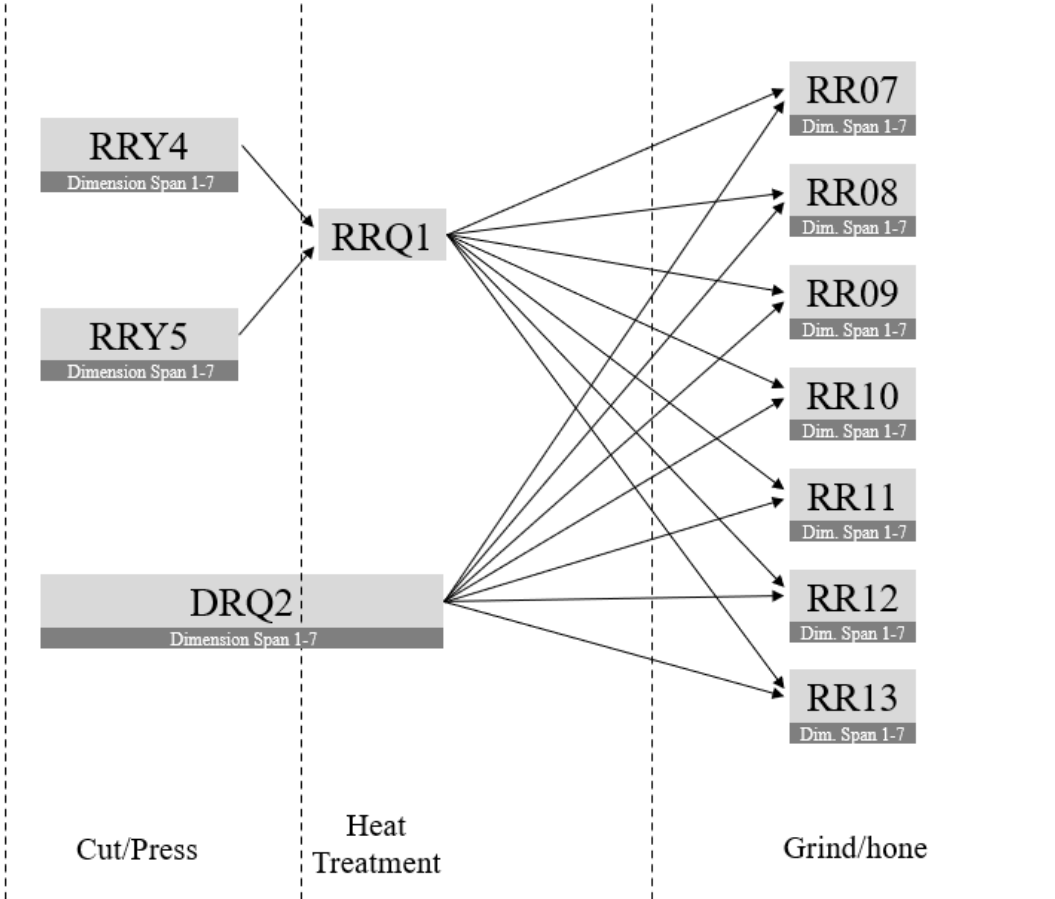


Figure 3 Flexible Flow Scenario

Understanding the current situation at SKF roller production is crucial as it provides a baseline from which the proposed production scenarios can be assessed. A comprehensive analysis of SKF's existing production environment, processes, and challenges ensures that the evaluation of the new production scenarios takes SKF's environment into consideration.

When evaluating the two different production scenarios, four key performance indicators (KPI) areas have been highlighted as important aspects for the comparison between the two scenarios. These include availability, stock, ease of planning & execution, and capacity utilization.⁵ A description of the four KPIs is shown in Table 2.

Table 2 Description of Scenario KPIs

KPI	Description
Availability	The number of orders of roller components that can fulfill the demand from the bearing assembly line (internal customer). 100% availability → The needed amount of the correct type of rollers is always ready when the assembly channel of the complete bearing needs them.
Stock	The number of rollers that sit in the inventory, the production, and the buffers in between the operations. Perfect stock level → no extra stock in inventory, production, and buffers than is needed to meet the availability goal.
Ease of planning & execution	The simplicity, efficiency, and effectiveness with which a production system can be planned, scheduled, and executed. High ease of planning & execution → Low effort required to plan production schedules and implement these plans into actionable tasks.
Capacity utilization	The extent and efficiency to which the production system's resources are being used. High-capacity utilization → The production system's resources are being used to its full potential.

1.4 Purpose & Research Questions

The purpose of this master thesis is to identify the most suitable production system for SKF's roller production. This entails an understanding of the current production system and a detailed evaluation of the two distinct production scenarios conceptualized by SKF, intending to help the company determine which production scenario aligns best with the production environment of the company. The outcome is intended to contribute to SKF's strategic decision-making, supporting that the production system will be longstanding.

To fulfill the purpose of this report and project, a primary and main research question (RQ) has been formulated and is called RQ4. To answer this question, three subsidiary research questions (RQs) have been developed.

⁵ (J. Schlager; J. Bengtsson, personal communication, January 25, 2024)

The first two questions have the purpose of investigating and describing the current situation at SKF as well as identifying issues related to the situation. Understanding the current state of the roller production is necessary as a starting point, as having background knowledge is much needed before it is possible to analyze and evaluate the two proposed production scenarios. By also identifying the issues related to it, it can later be analyzed what scenario could best manage these issues.

RQ1: What does the current situation look like for roller manufacturing at SKF?

RQ2: What problem areas can be identified connected to the current situation?

With a comprehensive description of the current situation and issues related to it, an analysis of the two scenarios can begin, where the main differences will be identified, leading to RQ3.

RQ3: What are the main differences between the two proposed production scenarios and how do they manage the identified problem areas?

Once the main differences have been identified and analyzed to see what production scenario best will mitigate them, it can be used as input in combination with an evaluation of the production scenarios towards the KPIs, for answering the final research question, RQ4.

RQ4: Which of the two proposed production scenarios for SRB rollers is most suitable for SKF?

1.5 Scope & Delimitations

This study centers on the SKF roller production system and its production flows, with a focus on the internal customers, namely the SRB assembly located in the D-factory. It is important to note that this study does not account for external customers, and as a result, the data collection is exclusively from internal customers, data such as demand on rollers, stock, and lead times. Additionally, the aftermarket is not factored into this study, meaning that the processes presented in the study are solely for the manufacturing of new products.

2. Methodology

This chapter outlines the methodology that has been implemented throughout the project. More specifically, the research approach and its strategy are presented, along with the methods used to collect the necessary data and analyze it. Finally, ethical considerations and the project process are described.

2.1 Research Approach

There are various ways to conduct research depending on the existing knowledge, prediction, and purpose. Bryman and Bell (2011) explain that the deductive theory approach is the most used method for working with empirical and theoretical data in research.

The chosen approach for this thesis was the deductive approach, as it was determined to be the most appropriate for the study. Theoretical data were collected from literature reviews from various sources, including Google Scholar and Scopus. In addition, empirical data were gathered through interviews, observations, and internal SKF documents, which were then analyzed and compared with the findings uncovered through literature reviews.

2.2 Research Strategy

According to Blaxter et al. (2006), the methodology of research can be broadly categorized into two distinct strategies: qualitative and quantitative. Typically, qualitative research is characterized by its reliance on subjective data, while quantitative research is grounded in objective data, primarily numerical and statistical in nature. Each type of data leads to different results, making the choice of an appropriate research strategy crucial for achieving the intended outcomes (Blaxter et al., 2006).

Blaxter et al. (2006) suggest that it is better to combine qualitative and quantitative methods instead of using them separately. This is because the four primary data collection methods such as documents, interviews, observations, and questionnaires can include both qualitative and quantitative aspects.

This thesis utilized a combination of qualitative and quantitative approaches in data collection. Qualitative data provided insights into the current situation at SKF, including the production environment and potential areas for improvement. It was used to identify problem areas and answer the research questions.

Quantitative data, on the other hand, was primarily collected for the current state map in the Value Stream Mapping (VSM). This data was crucial to ensure the VSM's validity and assist in understanding the current situation.

Furthermore, a Multi-Criteria Decision Analysis (MCDA) was conducted, based on the qualitative data collected from the interviews, the analysis of the VSM, how the different production scenarios tackle the identified problem areas as well as how they perform on each KPI. Consequently, this enabled the formulation of a well-founded recommendation for SKF on the most suitable production scenario for implementation in roller production, accompanied by a rationale for this choice.

2.3 Data Collection

The data collection of qualitative information mainly consisted of reading internal documents, making observations, and conducting interviews with personnel from SKF. These are three of the four main sources when collecting data, the last one is questionnaires which are not included in this research (Blaxter et al., 2006). Before conducting the interviews, various project-related documents were reviewed, this was deemed necessary to be able to get an initial understanding of the project as well as conduct the interviews effectively.

To gather quantitative data for the VSM, raw data were sourced either from the SKF's system or gemba walks.

2.3.1 Observations

In the context of lean, one main principle is “Go to the Gemba”, meaning “The Real Place”. This means that to fully understand a situation, it is important to see it with your own eyes (Liker and Meier, 2006). Therefore, the research was conducted at SKF to directly observe the processes and the flow of materials. Furthermore, "gemba walks" were utilized as the primary data collection method for the current state map in the VSM where this was feasible.

2.3.2 Interviews

Ryen (2004) highlights the effectiveness of qualitative interviews, for obtaining authentic and insightful information. This approach was chosen for the study to gain a comprehensive understanding and incorporate diverse viewpoints into the findings. Bryman (2012) mentions different types of qualitative interviews, where semi-structured interviews are one of them. The chosen methodology was the semi-structured interview, as Bryman (2012) suggests, offers flexibility in responses, and increases the possibility of having more discussion around the questions. Following Bosch et al. (2014), these interviews used a guide to balance structure and spontaneity. The guide allowed for adaptability in questioning and exploration of emerging topics, considering both the interviewer's and interviewee's interests and ensuring depth and relevance in the conversations (Bosch et al., 2014).

The interviewees consisted of carefully selected SKF personnel, working in various roles but all of them were relevant to roller manufacturing in some way. The respondents were selected based on their expertise on the topic of the study and its research questions. The selection process also considered the operational and strategic dimensions of their roles, ranging from supply chain planners to those in strategic positions.

It was considered important to conduct interviews with personnel who have different roles as this would mean getting a broader understanding and responses from the interviews and seeing the different opinions based on the roles of the personnel. This means that the study utilized a purposive sampling approach, as defined by Bell et al. (2019), where participants are selected based on their relevance in answering the research questions. Moreover, to some extent, the study also applied a snowball sampling approach. This approach involves participants suggesting other individuals who are relevant for the research interviews (Bell et al., 2019). A list of the roles of the interviewees is shown in Table 3 below.

Table 3 Roles of the Eight Interviewees

Interviewee Roles
<i>Process Owner</i>
<i>Process Development</i>
<i>Supply Chain Manager D-Factory</i>
<i>Business Development Rollers</i>
<i>Factory Supply Chain Manager</i>
<i>Supply Chain Planner</i>
<i>Supply Chain Planner</i>
<i>Production Manager</i>

Before the interview, interviewees received background information about the project and the interview questions, enabling them to prepare ahead and understand the topic of the interview. It was considered important to provide enough background information to each interviewee to be able to have discussions around the questions. Especially important for validity since each interviewee was asked to rank the KPIs explained in Table 2.

All interviews were audio-recorded, enabling the authors to listen to the interview afterward, allowing for a more comprehensive analysis of the interviewees' responses in the interview. Moreover, it reduces the possibility of bias when analyzing the data, leading to improved research quality and an increase in the readers' perception of the validity of the data collection (Bell et al., 2019). There was no hesitancy towards the recording of the interviews from the respondents. The interviewees are not mentioned by name in the report as this was the agreement before conducting the interviews.

2.3.3 Literature Review

Conducting a literature review is a crucial step in the research process, as it provides the foundational framework for validating research questions and structuring the research methodology, as discussed by Bryman and Bell (2011). Reviewing relevant literature related to the chosen subject is essential for constructing a rationale for the importance of the research and its proposed direction (Bryman & Bell, 2011).

The literature review served as a basis to delve deeper and increase the understanding of the research topic at hand, thus, the literature review was conducted in the early stages of the project. The literature is gathered from Google Scholar, Scopus, and relevant course books. The framework is mainly based on work from Bellgran and Säfsten (2010), Rother and Shook (2003), Liker (2004), and various works from Nigel Slack.

2.3.4 Current State Map

The current state map was conducted at the factory level, taking a specific product family into account, as suggested by Rother and Shook (2009). The reason why the current state map is important is to visualize and provide a further understanding of the current production system. The current state map data covers information about how materials and information move (Rother & Shook, 2003).

The data collection for the current state map was conducted through the collection of qualitative and quantitative data. Data was gathered through gemba walks, where the authors conducted door-to-door walks to observe and measure the flow of material. The gemba walk data was collected by utilizing a stopwatch as well as filling a datasheet with the collected data. The authors followed the production flow and asked questions to the operators to gain their insights and expertise. See Appendix A for a visualization of the datasheet.

However, it was not always possible to collect data from Gemba walks. Thus, when necessary, complementary data was collected from the Enterprise Resource Planning (ERP) system and machines-generated data from production. When collecting data from the ERP system, multiple SKF employees were involved in the process of gathering the data. Their expertise and knowledge of the system were utilized to ensure accurate and reliable data collection.

To gather data on the production planning process, the authors conducted interviews and observations of a supply chain planner's production order planning. After collecting all the necessary data, a current state map was drawn.

Rother and Shook (2003) mention the importance of conducting the VSM on products that undergo similar manufacturing processes. Thus, the VSM was conducted based on all products as they utilize the same type of resources when manufactured, meaning that all products are grouped into a single product family. However, the rollers are manufactured in different flows with different layouts, and not all flows are included in this study and project, which is why two current state maps were drawn, for RRY4-5 and DRQ2.

The VSM was initially created manually and then composed digitally. The symbols used in the VSM are inspired by Rother and Shook (2003), but the software used in this study had differences in the symbols to the one used in Rother and Shook's work (2003). Therefore, the symbols used are explained and visualized in Appendix B.

After conducting and analyzing the current state map, the authors gained an understanding of the current situation of the roller production system and aided in identifying problems. Usually, the goal after conducting the current state map would be to compose a future state map (Rother and Shook, 2003). However, in this case, it was not considered necessary as the purpose of the VSM was to gain a better understanding of the current situation and to identify issues related to it, rather than visualizing the future state of the two scenarios.

2.3.5 Multi-Criteria Decision Analysis (MCDA)

The process of the MCDA was carried out using the qualitative data that was gathered through interviews with the participants. As expressed by Belton and Stewart (2002), the essence of MCDA lies in its ability to tackle challenges posed by conflicting criteria and stakeholder views in complex decision scenarios. Thus, the interviewees were personnel from SKF with different roles. The respondents were provided with a detailed explanation of the KPIs included in the study, which are availability, stock, ease of planning & execution, and capacity utilization. They were then asked to rank the KPIs based on the level of importance they held for the production process. This provided the weights for each KPI.

To assess the impact of each scenario on the KPIs, a 3-point scale was utilized, as exemplified by Ishizaka and Newmery (2013). The levels were classified into three categories: low, medium, and high. Each category was clearly defined and assigned a corresponding quantitative value: 1 for low, 2 for medium, and 3 for high.

Furthermore, the problem areas identified in Chapter 4 served as a basis for comparing the effectiveness of the production scenarios in addressing these issues. This comparison facilitated the assessment of each scenario's performance against each KPI, which was based on observations, the identified problem areas from the interviews as well as the literature review. Scores were assigned to each KPI based on the performance of the production scenarios. Subsequently, the weighted scores for each KPI and production scenario were calculated by multiplying the KPI's weight by the scenario's score.

After conducting the MCDA, a result was drawn based on the scores attributed to each production scenario. This process provided quantified results reflecting the performance of each scenario, thereby facilitating the formulation of a recommendation for SKF.

2.4 Research Ethics

Bell et al. (2019) mention four ethical considerations that are relevant when conducting business research. These considerations are informed consent, privacy, preventing deception, and avoidance of harm.

Informed consent is essential as it ensures that participants in a study receive enough information to decide on their participation. In this study, respondents were provided with relevant information about the study before being given the choice of participating or not participating. This ensured that all respondents voluntarily participated.

Privacy is crucial to protect the participants' privacy, and in this study, participants were given the option not to answer questions or to withdraw their answers if the questions were perceived as sensitive. The respondents' names are also not included in the report, further protecting their privacy.

To prevent deception, the aim and the nature of the research should be shared transparently with the respondents and representatives from the case company. This was done in the study to ensure that the research was represented for what it is.

Researchers should also assess the possibility of harm to research participants and minimize this risk. In the study, potential risks of harm to respondents were assessed and minimized by again not including any names of the respondents in the report. A non-disclosure agreement was also signed with SKF to prevent any confidential information from being exposed. Regular meetings with representatives from SKF were held to further ensure this, as well as a final review before handing in the report.

2.5 Project Process

Figure 4 is a visual summary of the project process outlined in seven steps. Each step represents a critical milestone, and together, they form a strategic pathway intended to guide the project to a successful outcome.

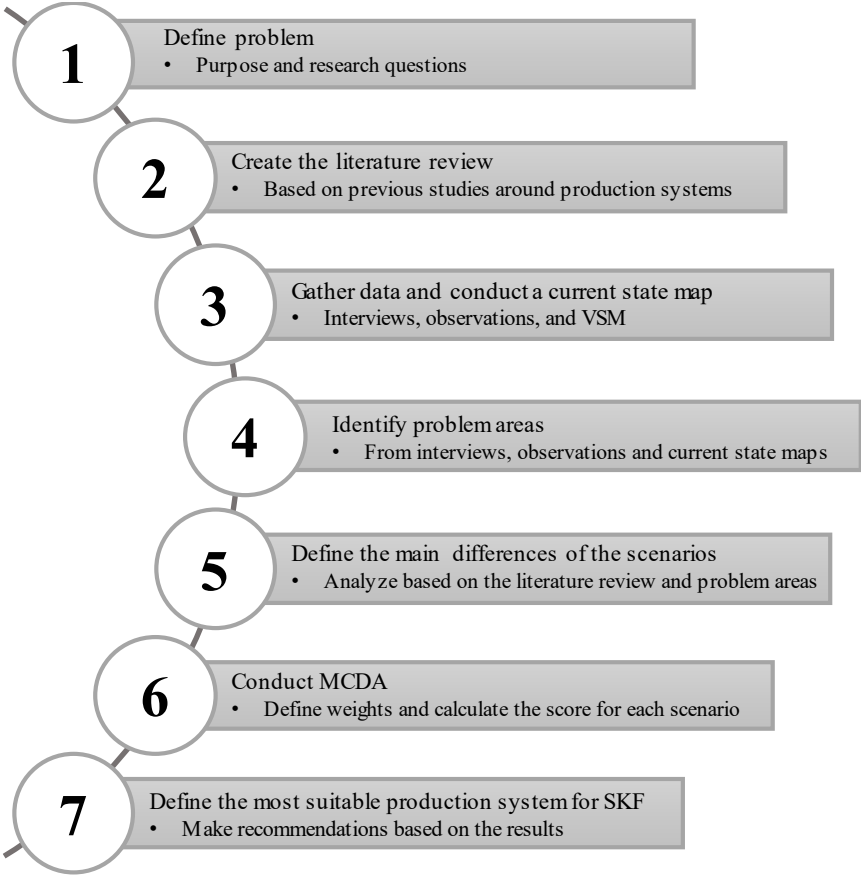


Figure 4 Seven Steps of the Project Process

3. Literature Review

In this section, a literature review guiding this thesis is outlined. It details the fundamental theories and concepts that inform the approach to the research questions. It plays a crucial role in shaping the analysis and interpretation of the findings. It includes an exploration of how concepts like volume and variety, production layouts, and push and pull systems influence when choosing the right production system. It also includes other areas of importance to a production system and strategy, e.g. constraints and various views on efficiency. Finally, theoretical explanations of VSM and how MCDA can aid in decision-making and evaluation are presented.

3.1 Production System

This chapter delves into factors influencing the selection of a production system. It offers an examination of various perspectives including volume and variety, layout and flow, and the approaches of push versus pull systems. Each section integrates theoretical insights with practical implications to guide the configuration of manufacturing processes.

3.1.1 Volume and Variety

Slack et al. (2013) present the impact of volume and variety in the design and management of manufacturing processes, where acknowledging the significance of both volume and variety is seen as crucial. The authors further explain the term "volume" describes the number of products manufactured, whereas "variety" refers to the range of product types or variants produced. Typically, these dimensions share an inverse correlation, suggesting that an increase in volume often leads to a decrease in variety, and vice versa (Slack et al., 2013). High-volume manufacturing processes emphasize efficiency and standardization, with the goal of producing large quantities of identical or similar items. Conversely, low-volume manufacturing processes are designed to support a wider array of products, prioritizing customization, and adaptability to fulfill varied customer needs (Slack et al., 2013).

Furthermore, the product-process matrix, presented by Slack et al. (2013) and shown in Figure 5, visually shows the volume-variety complexities, where the natural diagonal in the matrix highlights where the processes of companies should be positioned. When an organization's position is on this diagonal, it indicates a match where the manufacturing process is perfectly suited to the type of product being made. This alignment is crucial for efficiency, cost-effectiveness, and competitiveness. Companies to the right of the natural diagonal face excess capacity and higher costs, while those to the left struggle with capacity constraints and meeting demand (Slack et al., 2013).

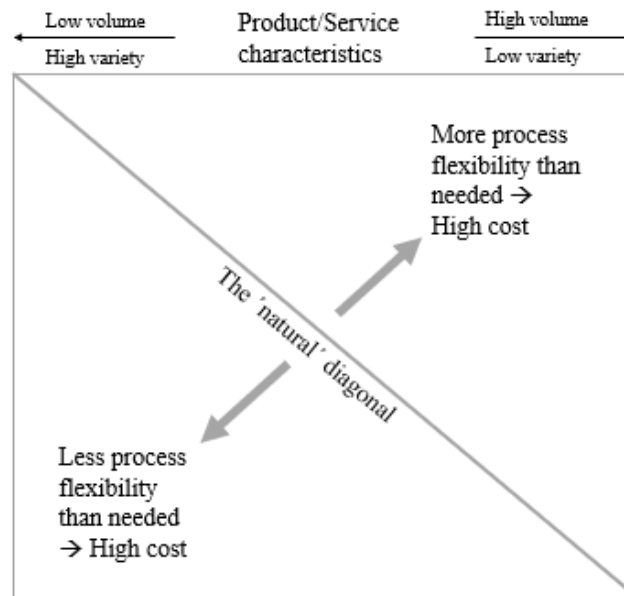


Figure 5 The Product-Process Matrix (Slack et al., 2013)

Slack et al. (2013) highlight that understanding the volume-variety relationship is essential for manufacturers to make strategic decisions about process design, resource allocation, and operational efficiency, aligning their production capabilities with market demands and business objectives. Whether a company opts for mass production with high volume and low variety or custom manufacturing with low volume and high variety depends on its competitive strategy and target market (Slack et al., 2013). Deif and ElMaraghy (2017) also highlight the area of strategic volume-variety management and the cruciality of operational efficiency and aligning production capabilities with market demands.

3.1.2 Layout and Flow

In the manufacturing industry, efficient operations are necessary for success (Slack et al., 2013). One critical aspect of optimizing manufacturing operations is the physical arrangement of resources, known as layout and flow. Proper layout and flow include the organization of facilities, machinery, equipment, and personnel to ensure maximum efficiency and productivity (Slack et al., 2013).

In a manufacturing setting, the layout and flow determine how materials, components, and finished products move through the production process. Optimizing these aspects can reduce the lead time, minimize material handling, and reduce waste (Slack et al., 2013). This aligns with Tomkins (1996), who emphasizes that it is crucial for the production layout to align with the organization's strategic visions, as this alignment enhances operational efficiency and supports the achievement of organizational goals.

The significance of flow to an operation depends, from the perspective of Slack et al. (2013), highly on its volume and variety. For example, when volume is very low and variety is high, flow will not be a major issue and the resources should be arranged so that irregular flow can be taken care of. On the contrary, when the volume is high and you have a lower variety, flow can become an issue, so the resources need to be arranged to cope with this regular and smooth flow (Slack et al., 2013).

There are four principal types of layouts in a manufacturing environment; fixed-position layout, functional layout, cell layout, and line (product) layout (Slack & Brandon-Jones, 2019). A description of each layout principle is presented below.

Fixed position: Slack and Brandon-Jones (2019) mention that this production setup is organized so that tasks and operations are executed in a singular location, with the product remaining stationary. In contrast, resources (such as personnel, materials, and machinery) are mobilized towards the product. This layout model is generally favored for extensive projects produced in limited or singular quantities, and the reason behind adopting a fixed position layout often comes from the product's excessive size or fragility, making it impractical to transport (Slack & Brandon-Jones, 2019).

Functional layout: A functional layout arranges together resources and functions that are similar to each other. This structure is commonly seen in manufacturing environments where large numbers of a diverse range of products are produced in small quantities (Zandin, 2001). Such a layout facilitates according to Slack and Brandon-Jones (2019) the straightforward supervision of equipment and facilities. It also has the potential to achieve optimal resource utilization (Bellgran & Säfsten, 2010). Additionally, it enhances flexibility in product mix and adaptation while maintaining resilience against operational disruptions. Nonetheless, the complexity of flow patterns in a functional layout is notable, as products may follow varied paths based on the specific operations required (Slack & Brandon-Jones, 2019). Due to the irregular and unique flow patterns throughout the factory, detailed planning and control are necessary for the functional layout (Zandin, 2001). This complexity often leads to extended lead times and complicates production planning, resulting in delays and queues for transportation across different groups of machines (Bellgran & Säfsten, 2010). Moreover, setup and WIP tend to be high as well as actual machining time constitutes only a small percentage of the actual lead time in the system (Zandin, 2001). Slack and Brandon-Jones (2019) further highlight that a functional layout could lead to high WIP or customer queuing.

Cell layout: Resources required for processing the same product families or components are allocated within specific cells. Each cell may then organize its resources following either a line layout or a functional layout. This variant of layout can offer an advantageous balance of cost-efficiency and flexibility within environments characterized by a considerable variety of products (Slack & Brandon-Jones, 2019). Compared to the functional layout, a cell layout shows a greater orientation towards streamlined workflows, thereby reducing the complexity typically associated with functional layouts (Slack et al., 2007). Additionally, it facilitates shorter throughput times and diminishes the number of planning points required relative to functional layouts (Bellgran & Säfsten, 2010). It also reduces the requirements for material handling, inventory levels, and spatial needs (Zandin, 2001). However, potential disadvantages include the significant costs associated with modifying the existing layout when changing to a cell layout, the necessity for additional equipment, and a reduction in overall facility utilization (Slack & Brandon-Jones, 2019).

Line layout: Also known as a product layout and organizes resources in alignment with the production process of the product. The production path for each product is fixed and follows a specific sequence. This layout is typically found and used in the mass production of standardized items (Slack & Brandon-Jones, 2019). It facilitates streamlined control over the production flow, leading to reduced costs per unit when operating at high production volumes. Nevertheless, this layout is characterized by limited flexibility and a high vulnerability to disruptions. Additionally, it may encounter challenges associated with the monotony of highly repetitive tasks (Slack & Brandon-Jones, 2019). Liker (2004) states, however, that its flexibility does not have to be worse; on the contrary, in a line layout, it is possible to achieve what the author describes as “real flexibility”, the ability to quickly respond to demand and to what the customer wants. By minimizing the lead time in a line layout, this real flexibility will be achieved (Liker, 2004). According to Liker and Meier (2006), the implementation of a continuous flow production system, that links process steps physically, can eliminate the need for inventory. Furthermore, it is a proven method for reducing stock levels in the production system (Liker & Meier, 2006). However, this requires a reduction of batch sizes as a necessary step toward achieving continuous flow (Liker & Meier, 2006)

These four different types of layouts do usually not operate in isolation. It is more typical to integrate various elements from more than one layout type, making it into a hybrid layout variant, or to implement different layout types across distinct segments of the production process (Slack & Brandon-Jones, 2019).

3.1.3 Push versus Pull Systems

The main difference between push and pull systems is where the motivation for the work process comes from (Jonsson & Mattsson, 2009). In push systems, outside factors decide when work should be done, while in pull systems, information from within the system itself guides when the work activities start. Push systems plan work based on what people outside the system want, but pull systems look at what's happening inside the system right now to make decisions (Khojasteh, 2016).

According to Jonsson and Mattsson (2009), materials planning is considered pull-oriented when the initiation and authorization for production and material movement come from the end user. Conversely, it is deemed push-oriented when these activities are not authorized by the end user but are instead started by a centralized planning authority (Jonsson & Mattsson, 2009). In push systems, activities are scheduled by a central system and completed according to central instructions, often leading to idle time, inventory, and queues due to mismatches between production stages (Slack et al., 2013). This leads to push systems regularly adding raw materials to the production flows, while pull systems only process parts when there's a real need for them. Hopp and Spearman (2008) point out that push systems follow a set schedule, but pull systems rely on the current situation in the factory to decide what to do.

Pull systems control how raw materials and parts enter production, which naturally keeps the amount of inventory from getting too high (Khojasteh, 2016). Cards or signals can be used to communicate when parts can be added. This means that there is a set limit on how much Work-In-Process (WIP) there can be. Push systems, on the other hand, don't have this kind of control because they work according to a fixed schedule (Khojasteh, 2016). In pull systems, the 'customer' workstation sets the pace and specification of work, pulling from the preceding workstation only as needed, effectively reducing inventory build-up (Slack et al., 2013).

The choice between using push or pull depends on what the product is and how customers place orders. For example, car companies often use pull systems because they let customers pick different features. But push systems are better for making lots of standard products, like TVs or pens, where manufacturing orders are based on forecasting what people want in the future. These systems create detailed production plans and lists of what materials are needed based on these forecasts (Khojasteh, 2016). If the firm is manufacturing large quantities of standard products, they would usually go for Make-To-Stock (MTS), rate-based, and push systems (Olhager & Rudberg, 2002). On the contrary, firms having low volume with a high variety of products would typically go for a Make-To-Order (MTO) setup, using pull in the production system.

3.2 Manufacturing Planning and Control

Manufacturing Planning and Control encompasses a wide range of activities within the logistics field, as defined by Jonsson and Mattsson (2009). It includes the planning, development, coordination, organization, management, and control of materials flows from the supply of raw materials to the delivery to end users. In manufacturing, various levels of planning are involved, with a common practice being “Manufacturing Resource Planning.”

Jonsson and Mattsson (2009) explain that Manufacturing Resource Planning is divided into two main segments: materials and capacity. The materials segment encompasses activities from production planning to procurement, while the capacity segment covers resource planning to execution and control. The significance of each segment changes with the planning horizon; materials planning holds greater importance in the short term, whereas capacity planning takes priority in the long-term context (Jonsson & Mattsson, 2009).

Furthermore, central to materials planning, according to Jonsson and Mattsson (2009), is the objective to match supply with demand in a cost-effective manner. Large differences between supply and demand can lead to either excess stocks or material shortages. This balancing involves two key dimensions: quantity (providing the accurate amounts demanded) and time (ensuring materials are supplied when needed). Aligning the quantity of supply with demand tends to be easier than mastering the timing of supply. Supplying materials too early can lead to unneeded capital being tied up, whereas delayed supply can cause shortages (Jonsson & Mattsson, 2009).

To help with planning and controlling operations, enterprise resource planning (ERP) systems are used (Slack & Lewis, 2015). The authors explain that ERP does not only contain information on the operations function but also almost every function within an organization. Furthermore, all relevant information throughout the organization could be brought together using the ERP system (Slack & Lewis, 2015). The authors further highlight that when the information is brought together, the system can inform planning and control decisions e.g. when certain activities should take place as well as where and who should be doing it. The system also provides information on what capacity is needed and so on. A well-integrated ERP system can help with decision-making throughout the planning and operation control operation and reduce the need for manual tasks outside of the system (Slack & Lewis, 2015).

3.2.1 Materials Planning Methods

As for materials planning, it includes a variety of methods, according to Jonsson and Mattsson (2009), where each is designed to determine the optimal timing for initiating orders and scheduling deliveries. These methodologies are adapted to suit either push or pull operational environments. In push environments, Materials Requirements Planning (MRP) is commonly used, guiding production, and purchasing decisions based on forecasted demand. In contrast, pull environments typically rely on re-order point systems, such as the two-bin system or kanban, which trigger replenishment based on actual consumption or demand (Lumsden, 2007; Jonsson & Mattsson, 2009).

MRP is a method for managing production and inventory. Ptak and Smith (2011) define MRP as a comprehensive system designed to address key operational questions: what items need to be produced or purchased, in what quantities, and when they should be delivered. The authors further highlight that MRP systems leverage current inventory levels to calculate necessary material amounts and their required timing. This methodology proves particularly beneficial for items characterized by dependent demand or for components that are needed irregularly but in significant volumes (Ptak & Smith, 2011; Axsäter, 1991). According to Jonsson and Mattsson (2009), implementing MRP requires production software that has a forward-thinking time horizon, detailed demand data for every component, thorough documentation of sub-components, up-to-date information on inventory quantities, pending orders, and backlogs, and precise lead times for each inventory item. (Jonsson & Mattson, 2009).

Jonsson and Mattsson (2009) further mention that a re-order point method triggers a new order once inventory levels hit a predefined threshold. This approach aims to ensure sufficient stock is available to meet demand throughout the lead time, including an additional safety stock to mitigate uncertainties. The method's straightforward nature and reliance on historical data for establishing re-order points make it particularly effective for managing items characterized by short lead times and consistent demand patterns (Lumsden, 2007; Jonsson and Mattsson, 2009).

Whereas in pull systems, mentioned by Liker and Meier (2006), kanban functions as a communication mechanism to regulate inventory by indicating when materials need to be replenished. The specific form of kanban employed can vary, tailored to the unique requirements of the operational context, with the goal of optimizing inventory control and the efficiency of replenishment processes (Liker and Meier, 2006).

In contrast to Kanban, Jonsson and Mattsson (2009) explain the two-bin system as being a physical application of the re-order point principle, utilizing two bins of varying sizes. Materials are drawn from the larger bin until it is empty, at which point a reorder is initiated. Subsequently, materials are used from the smaller bin, which contains a quantity sufficient to satisfy demand during the lead time, in addition to a safety stock, until the replenished materials arrive (Jonsson and Mattsson, 2009). This approach is especially effective for managing items with predictable demand and lower priority, often referred to as class C products within the ABC classification system (Stevenson, 2005).

3.3 Theory of Constraints

Effective planning necessitates a careful balance between the delivery requirements and the production capabilities, including available inventory (Jonsson & Mattsson, 2009). This balance highlights the necessity to acknowledge the constraints inherent in the production system. Jonsson and Mattsson (2009) identify manufacturing capacity as the foremost constraint that must be addressed. However, they also emphasize the importance of considering other factors such as storage space, transportation resources, and the capacity of suppliers.

The Theory of Constraints (TOC) is a prominent methodology that addresses capacity constraints within material flow planning (Jonsson & Mattsson, 2009). This approach focuses on identifying and maximizing the use of bottlenecks within the production system, thereby aligning the entire system's operations with these constraints. Over time, this method has been refined to adopt a broader constraint-based perspective, moving beyond only focusing on bottlenecks (Jonsson & Mattsson, 2009).

According to Jonsson and Mattsson (2009), a constraint is characterized as any factor that negatively impacts and restricts the efficiency of a system, whereas a bottleneck refers to a stage in a process, such as a production line, where the capacity is less than the capacities of preceding and subsequent stages, resulting in a reduction in overall lead time.

The “drum-buffer-rope” is a concept first presented by Goldratt & Cox (1992), which is an operational technique within TOC that serves as a management tool for handling production rates and bottlenecks. The drum sets the pace for production and determines the maximum speed at which the production system can produce, which is based on the capacity of the bottleneck. The rope ensures that other parts of the process are synchronized with the drum so that the production is balanced and efficient. The buffer is a strategically placed location before the bottleneck to prevent any disruption in its operation (Goldratt & Cox, 1992).

The throughput of a production process is determined by its slowest step, the bottleneck, which sets the maximum production pace during a specific time (Li et al., 2009). It is therefore important to integrate push and pull systems at the bottleneck, ensuring it is always operating. According to Olhager and Östlund (1990), this necessitates a strategy where operations leading up to the bottleneck are driven by a push approach, ensuring the bottleneck is always supplied with work. Conversely, operations downstream of the bottleneck should adopt a pull strategy, drawing work through the system as needed based on demand.

According to Jonsson and Mattsson (2009), the core principle of TOC is the recognition that all systems are subject to constraints. This recognition not only highlights the inevitability of constraints within any system but also identifies them as opportunities for ongoing improvement. As Jonsson and Mattsson (2009) elaborate, the identification of constraints within a system is crucial for aligning production and material flow with customer demands. Achieving this alignment requires a structured approach, for which Jonsson and Mattsson (2009) propose five essential steps:

1. Identify the constraint.
2. Exploit the constraint.
3. Subordinate everything else.
4. Evaluate the constraint.
5. Go back to the first step.

3.4 The Bull-Whip Effect

The bull-whip effect is a common problem in the supply chains of companies. It is defined by Singh (2018) as a phenomenon where fluctuations and inefficient asset allocation happen due to changes in demand in the supply chain. Companies attempt to forecast demand by collecting a large amount of resources and raw materials to meet customer requirements (Preston, 2022). However, when moving up the supply chain, variations tend to increase, leading to issues such as time, cost, and inventory management (Preston, 2022). According to Jonsson and Mattsson (2009), variations in demand tend to double for each step in the supply chain. Customer demand distortions on the entire supply chain are visualized in Figure 6 below.

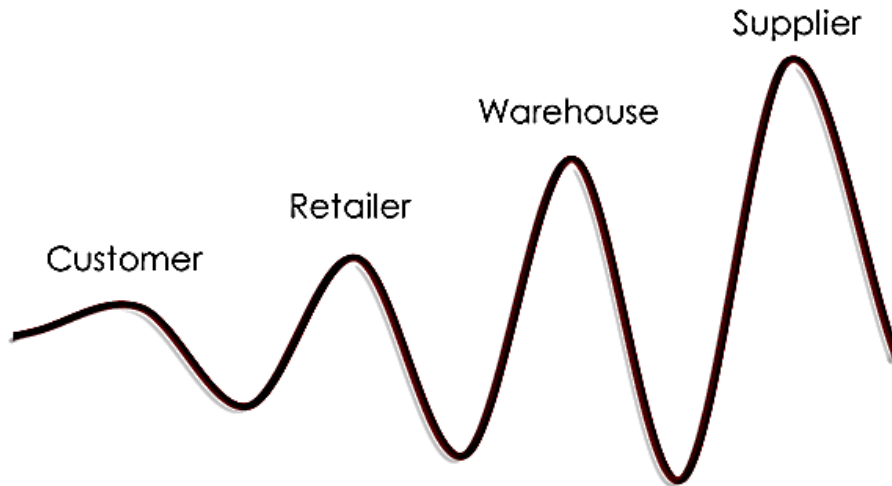


Figure 6 Illustration of the Bull-Whip Effect (Preston, 2022)

Slack et al., (2013) say that one of the common reasons causing the bull-whip effect is miscommunication in the supply chain. Jonsson and Mattsson (2009) summarize the main reasons for the bull-whip effect as well:

- Large order quantities
- Few large customers
- Planning and control are not aligned
- Price fluctuations along with promotions
- Lack of communication and information sharing

The bull-whip effect can cause companies to experience either a shortage or surplus of inventory, both of which can have unfavorable consequences (Preston, 2022). The authors further mention that a shortage of inventory can result in poor customer relations due to lower order fulfillment, while a surplus can tie up capital and lead to wastage.

Different strategies can be used to counteract the causes of the bull-whip effect. Lee et al. (1997) categorize these strategies as information sharing, channel alignment, and operational efficiency. See Table 4 for an explanation of the respective strategy.

Table 4 Explanation of Strategies Used to Counteract the Bull-Whip Effect (Lee et al., 1997)

Strategy	Explanation
Information Sharing	Timely transmission of information from a downstream site to an upstream site is important to meet demand requirements.
Channel alignment	Managing the pricing, transportation, inventory planning, and ownership across various sites in the supply chain to ensure smooth coordination.
Operational efficiency	Ways to enhance the performance such as minimizing costs and lead time.

3.5 Flow- versus Resource Efficiency

Modig and Åhlström (2012) define flow efficiency as the focus on the movement of a product through a system and the addition of value to the product via various activities. Flow refers to the transition between activities, aiming for each transfer to reach its intended recipient accurately, in the right measure, and at the right time (Bellgran & Säfsten, 2010). Enhancing flow efficiency through the elimination of activities that do not add value results in a reduction of costs (Rahani & Al-Ashraf, 2012).

On the contrary, Modig and Åhlström (2012) define resource efficiency as having a focus on utilizing the resources to achieve the highest possible output. This approach is based on the principle of getting the most out of the available resources, treating elements of the production system as assets that need to be fully utilized. This perspective is according to Modig and Åhlström (2012) common in traditional production environments where maximizing output and reducing costs are key priorities. However, the authors are implying that this approach can lead to inefficiencies such as high turnover and reduced innovation due to the high focus on productivity at the expense of creativity and strategic thinking.

Achieving success in lean manufacturing, according to Modig and Åhlström (2012), necessitates a comprehensive perspective that encompasses both the production resources and the flow. Modig and Åhlström (2012) highlight that many organizations overly concentrate on resource efficiency, frequently overlooking the significance of flow efficiency. To clarify and underscore the importance of optimizing both resource and flow efficiencies, Modig and Åhlström (2012) introduced a matrix presented in Figure 7, which categorizes the various states an organization may find itself in, based on the emphasis it places on resources and flow efficiency.

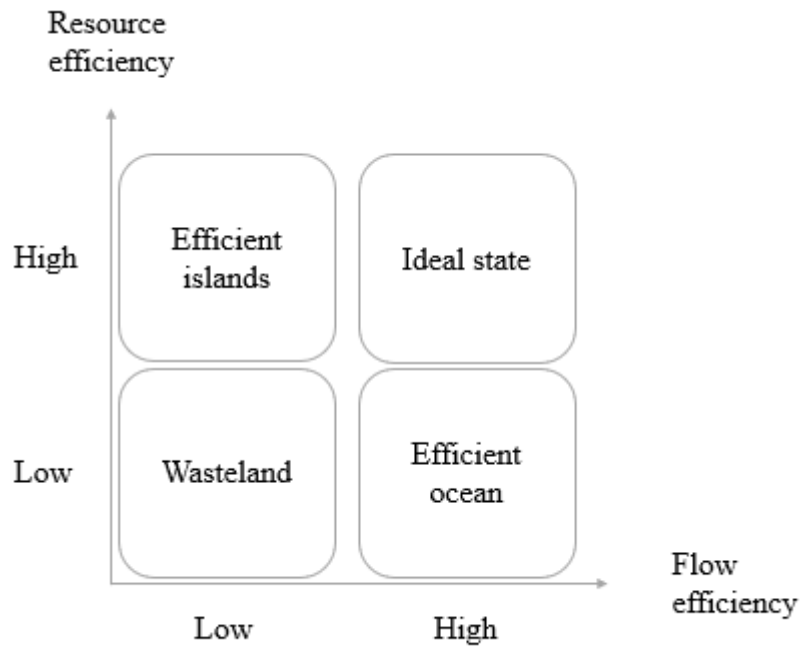


Figure 7 Efficiency Matrix (Modig & Åhlström, 2012)

Modig and Åhlström (2012) categorize the different states as Wasteland, Efficient islands, Efficient ocean, and the Ideal state. These states, as explained by Modig and Åhlström (2012), are described below.

Efficient Islands

When there is high resource efficiency but low flow efficiency, this state is referred to as an efficient island. In this state, an organization's processes operate in isolation, prioritizing individual performance and the maximization of resource utilization within each distinct process. While a focus on resource efficiency can lower the production costs of goods, it can also lead to significant waste due to waiting times and increased inventory levels. This inefficiency in flow can introduce hidden costs, offsetting the benefits gained from resource optimization (Modig & Åhlström, 2012).

Efficient Oceans

On the contrary, when having high flow efficiency but low resource efficiency, this state is called efficient oceans. Here, the organization doesn't view processes as separated, but rather as components of an integrated system geared towards achieving efficient flows that pleases customer needs. This approach prioritizes customer satisfaction, with resources being deployed not for maximal efficiency but rather in response to customer demands. Resource overcapacity is maintained in such systems, ensuring the organization's capability to always meet customer requirements, even at the expense of not utilizing resources optimally (Modig & Åhlström, 2012).

Ideal State

The ideal state is attained when an organization simultaneously achieves high resource and flow efficiency. Achieving this represents a challenging objective, primarily because every system inherently contains variations that cannot be completely eliminated. These variations must be carefully managed while striving to optimize both resource use and the smoothness of operational flows. The complexity of reaching this ideal state lies in the need to address and integrate these variations into a coherent strategy that enhances both efficiency dimensions (Modig & Åhlström, 2012).

Wasteland

Wasteland is explained as a state where organizations should work to stay out (Modig & Åhlström, 2012). Here, both resource and flow efficiency are low, entailing that an organization is not performing well in any of the two. It reduces capacity utilization and leads to long lead times with low customer satisfaction (Modig & Åhlström, 2012).

3.6 Value Stream Mapping (VSM)

Lean manufacturing is characterized by its focus on enhancing value by eliminating waste, it plays an essential role in reducing the time it takes to move products from production to the market (Locher, 2008). Rother and Shook (2004) describe a value stream as every activity required to convert raw materials into finished goods for the customer, including both value-adding and non-value-adding activities. This approach requires the careful management of intertwined flows of information and materials specific to a value stream (Rother & Shook, 2004).

VSM, originating from Toyota's Production System, is a strategic tool designed to map and enhance value streams (Liker and Meier, 2006). It provides a visualization of both material and information flows as a product progresses through the production system, pinpointing potential areas for improvement (Bellgran & Säfsten, 2010). VSM was developed as a method to describe these flows, and it makes the current production processes transparent, aiding in the identification and elimination of waste. This process paves the way for proposing an optimized future state of operations. The methodology behind VSM analysis, as outlined by Rother and Shook (2002), is seen in Figure 8, detailing the steps involved in conducting a VSM analysis.

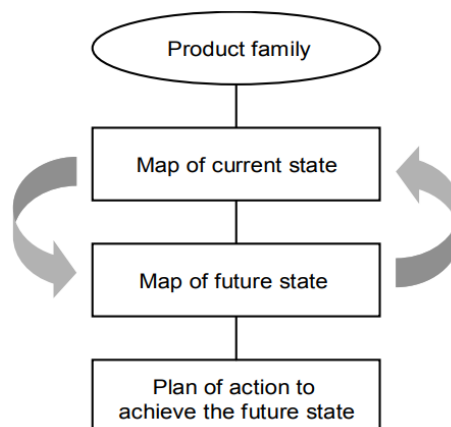


Figure 8 Steps Involved in VSM Analysis (Rother & Shook 2002)

3.6.1 Waste

In a VSM, waste identification is crucial and is categorized into two main types. The first type, known as "necessary waste," includes activities that, although not value-adding, like training, testing, and other essential tasks, are indispensable to the operation. While it would be beneficial to eliminate these, it's not always practical. The second type encompasses eight specific activities that directly fail to add value. Eaton (2013) and Liker and Meier (2006) outline these eight distinct forms of waste, which are presented in Table 5.

Table 5 Eight Wastes (Eaton, 2013; Liker and Meier 2006)

Waste	Description
Overproduction	Items are produced in quantities larger than required or before the customer's actual demand arises.
Waiting	Workers are hindered from executing their duties due to equipment failures, bottlenecks, and similar problems.
Defects	Producing goods that contain flaws or defects.
Motion	Operators' actions that do not contribute value, including searching for or retrieving tools.
Transport	Moving work-in-progress (WIP) within a process or between different processes.
Overprocessing	Carrying out manufacturing processes beyond what the customer requires, leads to a product quality that surpasses necessary standards.
Inventory	Extended lead times, outdated inventory, and increased storage costs arise from excess work in progress (WIP) or finished products.
Talent	Not taking advantage of the creativity, ideas, and skills of employees.

According to Taiichi Ohno, who is considered to be the father of the Toyota Production System, overproduction is the primary source of waste because it leads to other types of waste (Liker & Meier, 2006; Slack et al., 2013). When a company produces in advance or more than what their customers demand in each process of the production system, it eventually results in having excess inventory at some point in the later stages. The surplus materials remain unused and wait to be processed in the next operation, leading to waste accumulation and an increase in costs because of capital being tied to storage (Liker & Meier, 2006). The authors further mention that it is possible to deliver high-quality products at a lower cost without having a large inventory in the warehouse.

Potential reasons for overproduction may include producing according to oversized economic batches, creating inventory to cope with defects, and machines operating too quickly (Chiarini, 2012). Ways to countermeasure the development of overproduction could be firstly to manufacture according to the pace of takt time. Manufacturing according to the takt time means to produce at a pace that aligns production with customer demand (Chen et al., 2019).

According to Liker (2004), takt time is a concept mostly used within pull-based production environments, where the demand is pulling the production, and when flow efficiency is considered a problem. The same author is also saying that the main challenge when utilizing takt time is to determine the customer demand, which in production environments with a variety of products with varying demands is a hard task. Addressing this challenge involves recognizing that takt time serves as a guideline, and understanding the implications of deviating from this guideline on production, with the first point being that when demand is varying, the cycle times for producing do not change if they are standardized, making the only way to deal with it by increase or decrease production time (Liker, 2004).

Furthermore, reducing the amount of possible WIP in the production system is another way of reducing overproduction according to Chahal and Narwal (2017). Hopp et al. (1990) explain that reducing lead time can result in lowering the WIP, which leads to a reduction in overproduction and excess inventory. Reducing lead time and WIP can be done by implementing a pull system, such as kanban, which can show areas of overproduction and lack of synchronization (Chahal & Narwal, 2017; Slack et al., 2013).

Liker and Meier (2006) describe transportation as a wasteful activity that is associated with moving parts between processes. For instance, this may involve the transportation of WIP from one location to another for processing purposes. Additionally, transportation may also entail the movement of materials and finished goods in and out of inventories, as well as between different processes (Liker & Meier, 2006).

According to Dennis (2007), this type of waste is closely linked to poor factory layout, large machinery, or ordinary batch production. This creates a need for transporting the goods between activities. Another factor that increases the need for transportation is excessive inventory which causes a need to move products from one warehouse to another or move products from a warehouse to a production process (Chiarini, 2012).

3.6.2 Current State

Rother and Shook (2004) advise initiating the mapping of the current state by identifying a particular product family for analysis. The selection of the product family can be efficiently conducted by grouping products that undergo similar manufacturing processes and utilize the same equipment. Those that share common resources are classified as a single-product family. Additionally, preference should be given to products exhibiting stable demand and consumption patterns over the year for a more accurate and relevant analysis (Rother & Shook, 2004).

During the mapping process, according to Rother and Shook (2004), the individual(s) responsible begin by walking the selected product's journey from the entrance to the exit of the factory, known as gemba walks, gathering essential data from both material and informational perspectives. The collected flow and information are subsequently drawn by hand, employing commonly recognized symbols to highlight specific details. While these symbols may vary between companies or VSMs, it's crucial to ensure that all participants understand the meaning of each symbol used (Rother & Shook, 2004).

A diverse array of data can be collected while observing the flow of the selected product. To streamline this process strategically, Rother and Shook (2004) advise preparing a guide in advance, detailing the types of data to be gathered. This guide should then be employed consistently across each process step of the current state. The compilation of this data and the subsequent creation of the current state map establish a solid foundation for envisioning and planning the future state (Rother & Shook, 2004).

3.6.3 Future State

After finishing the current situation map, it lays the foundation for building the future state map. Rother and Shook (2004) assert that successfully creating this map requires answering eight specific questions, as shown in Table 6 below.

Table 6 Eight VSM Questions (Rother & Shook, 2004)

Question	Definition
1.	Determine the takt time based on the working hours of processes nearer to the customer.
2.	Decide whether to use a finished goods supermarket for customer pull or ship directly.
3.	Identify opportunities for implementing continuous flow processing.
4.	Determine where supermarket pull systems are required to manage upstream production.
5.	Choose a specific point in the production chain for scheduling.
6.	Plan how to balance the production mix at the pacemaker process.
7.	Define the consistent work increment for release and retrieval at the pacemaker process.
8.	Identify necessary process improvements to achieve the flow outlined in your future-state design.

These questions are crucial for identifying potential improvements in the existing workflow. Bicheno et al. (2011) describe the analysis of the current state as a mechanism for generating ideas intended to refine the value flow.

3.7 Evaluation of Production Systems

Evaluation of production systems is of high importance according to Bellgran and Säfsten (2010), either if it’s a system already employed or a future system that will be implemented. As described by Groten and Gallego-Garcia (2021), the manufacturing processes are continuously evolving, making the evaluation and improvement of production systems important, even essential, to be able to adapt to market demand and new technologies in the market.

3.7.1 Performance Objectives

Incorporating customer requirements into operational strategy decisions is essential for any company (Slack & Lewis, 2015). Establishing objectives that not only align with operational needs but also mirror customer expectations is critical for ensuring this alignment. The framework of five generic performance objectives presented by Slack & Brandon-Jones (2019), and further emphasized by Bellgran and Säfsten (2010), serves to connect customer needs with business operations, providing a structured approach to achieving strategic alignment. The five objectives are *Quality, speed, dependability, flexibility, and cost*.

According to Slack and Brandon-Jones (2019), the significance of the objectives varies across businesses, and this depends on the individual operating environments of the company. For one company focusing on providing rapid deliveries to its customers, priorities should be within the speed objective, e.g. lead time, whereas for another company whose customers demand customized products, the objective of flexibility would be of greater importance. It's crucial to recognize that within a single company, the importance of these objectives may vary among different product lines, illustrating the need for a tailored approach to align operational strategies with specific market demands and internal capabilities (Slack & Brandon-Jones, 2019).

Slack and Brandon-Jones (2019) explain each performance objective as described below.

Quality is important in assessing customer perceptions of a product. Quality evaluation serves as both an external measure of meeting market expectations and an internal one for process improvement. Enhancing quality in production reduces costs by decreasing errors and rework, thereby stabilizing processes, and allowing personnel to prioritize other things rather than working on corrections (Slack & Brandon-Jones, 2019).

Speed is highlighted as crucial by Slack and Brandon-Jones (2019), for both private and business customer viewpoints. It focuses on reducing lead times across all processes to enhance efficiency. The emphasis on speed involves streamlining operations and making faster, informed decisions. Slack and Brandon-Jones (2019) imply that increasing the speed may lower the risks connected to planning. By shortening the time-to-market, uncertainties can be reduced. According to Slack and Brandon-Jones (2019), one of the key reasons why speed is crucial in reducing inventory levels is that materials spend a significant amount of time in stock while navigating through the production system. This means that the longer it takes for products to move through each process, the more time they will spend waiting, resulting in higher inventory levels (Slack & Brandon-Jones, 2019).

Dependability helps evaluate and ensure, according to Slack and Brandon-Jones (2019), that services, products, or operations are delivered within a specified time frame. Its absence can deny the benefits of high speed and quality. For example, in a context where the customer has high expectations and there is a delay happening, this could lead to increased operational costs and impact speed by necessitating corrective actions. Dependable operations allow for a focus on enhancing value-adding activities, thereby stabilizing operations, reducing costs, and preserving speed and quality (Slack & Brandon-Jones, 2019). Furthermore, failing to meet promised delivery dates can result in customers seeking out other companies to purchase from, making dependability even more crucial to organizations (Slack & Lewis, 2015).

Flexibility assesses a business's adaptability to changes in demand, including shifts in consumer interests or the need to increase/decrease production, so-called volume-flexibility (Slack & Brandon-Jones, 2019; Bellgran & Säfssten, 2010). Enhanced flexibility reduces response times to changes, thereby improving operational efficiency and customer satisfaction by quickly addressing shifts in demand (Slack & Brandon-Jones, 2019). Furthermore, Bellgran and Säfssten (2010) imply that organizations can utilize flexibility to minimize sensitivity to disturbances, and handle disturbances in the production system, enabling manufacturing to take place elsewhere.

Cost, as the final performance objective, historically stands as the most commonly emphasized and used objective. Although current market competition encompasses a broader range of factors, cost efficiency continues to play a critical role by directly influencing the profit margins of companies (Slack & Brandon-Jones, 2019).

Figure 9 shows a model called the sand-cone model, which, according to Slack and Lewis (2015) and Bellgran and Säfssten (2010), describes that the performance objectives are cumulative, meaning that they build on each other. The fundamental objective of quality, followed by dependability and speed, needs to be met before it is possible to compete on cost and flexibility (Slack & Lewis, 2015; Bellgran & Säfssten, 2010).

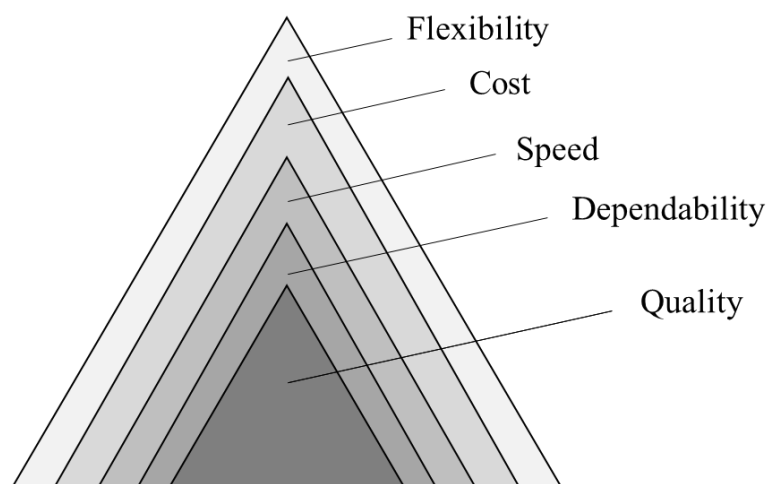


Figure 9 Sand-Cone Model Based on Slack and Lewis (2015) and Bellgran and Säfssten (2010)

According to Dangayach and Deshmukh (2001), it is widely recognized that the focus of operations strategies is on achieving competitive advantage through cost, quality, dependability, and flexibility. These performance objectives should align with the company's long-term strategic goals, whereas operational objectives focus on short-term targets and are typically more quantifiable (Doran, 1981). Connecting to what Pozo et al., (2017) say, that operations strategy is shifting from a market-based approach, which views operations as highly adaptable systems aiming to meet market demands, to a resource-based vision. This newer approach advocates for a focus on developing and utilizing a company's operational resources to gain a competitive edge, suggesting that internal capabilities are crucial for achieving long-term success. By using the performance objectives, the company could transform long-term goals into short-term and operational objectives (Doran, 1981).

3.7.2 MCDA

Gamper et al. (2006) and Linkov and Moberg (2012) express MCDA as a tool for managing complex decision problems, aiming to identify the most optimal solution by considering the interests and preferences of all stakeholders, alongside practical information. This approach strives to achieve a consensual solution that aligns with the needs and expectations of everyone involved in the decision-making process, thereby facilitating a more manageable decision-making landscape by considering multiple criteria across all dimensions simultaneously (Gamper et al., 2006; Linkov & Moberg, 2012).

Belton and Stewart (2002) and Bączkiewicz et al. (2021) explain that the process of MCDA involves evaluating and ranking options based on these criteria, where importance is assigned through systematic grading and weighting for each criterion. This allows for a comparative analysis of the options to determine the most favorable outcomes. The essence of MCDA is its ability to tackle challenges posed by conflicting criteria and stakeholder views in complex decision scenarios. It assists decision-makers in organizing and synthesizing complex and conflicting information, leading to decisions that minimize the potential for post-decision regret by ensuring that all relevant factors have been considered (Belton & Stewart, 2002; Bączkiewicz et al., 2021).

4. Current Production System

This chapter provides answers for RQ1 and RQ2, starting with information about the production environment that SKF is operating in for their SRB product. Following with the current production- and information flow of SRB rollers, along with the current state map, finishing with the identified problem areas. All information in this chapter is collected through observations and interviews with different employees of the company and is analyzed based on the literature review.

4.1 Production Environment

The manufacturing of rollers is significantly impacted by the production of SRB, and the rollers stand for approximately one-third of the total cost of an SRB, making it one of the more crucial components in the assembly of the complete bearing. A comprehensive understanding of the production environment, encompassing both roller and SRB manufacturing, is vital for grasping the broader market and operational context in which the company and its roller production activities are situated. This includes the production strategy currently employed, the distribution network and bearing assembly of the SRB, and the process of manufacturing rollers. For the distribution network, different types of forecasts utilized in this context, the sales- and shipping forecast, further described later in this section, will be elaborated. This must also include considerations of the bullwhip effect, where forecast inaccuracies and variability in demand lead to amplified fluctuations in upstream production activities (Singh, 2018; Preston, 2022).

4.1.1 Production Strategy

SKF has used a production process called Channel Concept for several years. Channel Concept was first introduced in the late 80s and is a manufacturing process that represents a significant shift from process-oriented or functional layout to streamlined, flow-oriented, and lined-based layout, expressions described in chapter 3.1.2. This approach aimed towards a change from a push to a pull philosophy, intending to improve responsiveness to market demands. The goal was to enhance customer service levels, simplify and make production flows more visible, reduce lead times and inventory levels, minimize total costs, and establish a pull system within the production framework (SKF Channel concept booklet, February 19, 2024).

However, according to an interviewee, this flow-oriented mindset is noticeably shifting towards a production system focusing more on resource efficiency. After observations, it appears the roller production setup utilizes both push and pull techniques, rather than a true pull system which according to Hopp and Spearman (2004) is when the system only produces when there is an actual need. Orders are pulled from the system, that has calculated the demand that is necessary for an order, afterward this order can be changed and increased to a higher or lower quantity, decided by a supply chain planner. According to Jonsson and Mattson (2009), a pull system usually works with a re-order system of some kind, it can be a kanban card or a calculated re-order point. Right now, the production orders are based on calculations from the MRP system, which usually signifies a push system (Jonsson & Mattson, 2009).

The manufacturing of SRB follows an MTS strategy. This strategy is primarily driven by forecasts, reflecting a proactive approach to production planning where items are produced based on anticipated demand. The volume produced is considered to be high, which aligns with Olhager and Rudberg (2002) that when having large quantities of standard products, an MTS strategy is preferred.

On the contrary, the manufacturing of rollers is viewed as having an MTO strategy, in line with the above paragraph saying that orders are being pulled from the system, taking the demand from the SRB and converting it to production orders for rollers. However, an MTO strategy is according to Olhager and Rudberg (2002) often used when the production system is using a pull method, which is not the case since the demand that comes from the SRB is changed, thereby having a finished goods location where rollers are placed before sent to the bearing assembly. This does in fact, in alignment with Olhager & Rudberg (2002). go more towards a push system with a MTS strategy.

Furthermore, the production of rollers is considered to be of high volume, with a maximum capacity of around 1,3 million per month. Variety on the other hand, which according to Slack et al. (2013) refers to the range of product types or variants produced, is considered to be a bit narrower with around 130 different roller variants, especially if compared to the SRB which includes around 8200 variants.

4.1.2 Distribution Network of SRB

The distribution network for SRB extends from an on-site finished goods warehouse to the end consumers. Intermediate nodes within this network include regional and local warehouses, along with industrial distributors. Examining inventory levels across these nodes reveals that the Gothenburg warehouse maintains approximately one month's worth of finished goods inventory. Similarly, four regional warehouses hold 1.5 months' worth of stock, while all local warehouses are stocked with about half a month's worth of goods. Industrial distributors, which represent the company's largest customer base, and end consumers alike, typically keep around one month's worth of inventory on hand. Such an inventory management strategy can be seen as a way of buffering against demand variability, reflecting a typical response to mitigate the impacts of the bullwhip effect (Preston, 2022).

For a more comprehensive understanding, this distribution network is illustrated in Figure 10 below. Overall, the downstream supply chain from SKF encompasses about five months' worth of finished SRB inventory, with SKF warehouses accounting for three months of the total amount.

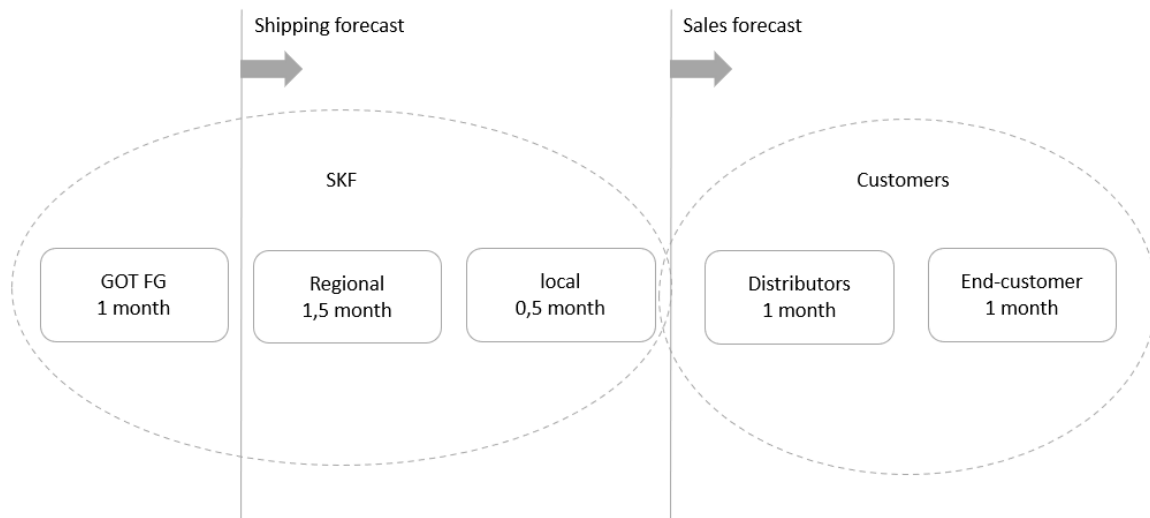


Figure 10 Distribution Network of SRB

Within the Gothenburg factory's planning framework, two distinct types of forecasts are utilized: the sales forecast and the shipping forecast. The sales forecast projects the value of goods expected to be invoiced from SKF warehouses to customers, providing insights into anticipated customer demand. The shipping forecast shows expected shipments from the Gothenburg factory, either to the regional or local warehouse or directly to customers, offering a view into logistics and distribution requirements.

These forecasts play a critical role in the production planning for SRB and its roller components, with a direct influence on manufacturing and supply chain operations. The sales forecast primarily focuses on customer demand, showing market stability and consistent demand patterns if looking historically.⁴ However, it's noted that variability in demand tends to increase upstream, indicating more clear fluctuations in production-related activities than what sales data alone might suggest. This phenomenon of increased upstream variability is a direct manifestation of the bullwhip effect, where demand increases for each step back in the supply chain (Jonsson & Mattsson, 2009).

The shipping forecast, by incorporating regional and local warehouses into its analysis, reveals even more variability, contributing further to the bullwhip effect (Jonsson & Mattsson, 2009). This is particularly significant for roller production, which precedes SRB assembly, and thus experiences greater variation, partly due to one bearing consisting of between 40-60 rollers. Managing this variation requires increased effort in planning and logistics to ensure smooth downstream operations.

Manufacturing often perceives high volatility in demand in business fluctuations since both real customer consumption of bearings and changes in the stock value throughout the whole distribution network are added together. Hence, when the market turns down, both stocks and bearing consumption in the market are reduced.⁴

However, the rollers are an internal supplier to the SRB, supplying the components based on actual customer orders derived from the SRB production and not on forecasted demand, which, according to Jonsson and Mattsson (2009), should not impact and contribute to an increase in the bull-whip effect. The reason for seeing a greater variation in roller production is therefore most likely due to a lack of communication and information sharing or having too large order quantities produced, which are two of the main reasons for the bull-whip effect (Jonsson & Mattson, 2009). For the roller production, batches of a minimum of 10,000 units are being produced which can be considered as a high amount, only showcasing that this might well be one of the reasons for the bullwhip effect happening in the supply chain.

Currently, the roller production serves four distinct bearing assembly channels, these assembly channels are known as internal customers. A fifth assembly channel is currently under construction, distinguished by the ability to assemble smaller batches of rollers, thereby accommodating a higher flexibility and frequency. The key feature enabling this channel's flexibility is the automated setup function of its machinery. This eliminates the need for manual adjustments, thus facilitating the handling of various types of rollers and components without significant effect on machine uptime.

4.1.3 Production Process of Rollers

The Gothenburg plant contains several manufacturing flows that produce rollers. Although each flow follows a similar process, each differs in terms of material movement. Some production flows share resources and move materials manually using forklifts, while others have continuous flow using conveyor belts to move material and do not share resources and machinery with other production flows.

The production of rollers begins with the procurement of raw materials, specifically bars, from external suppliers. Upon arrival at the factory, the first operation (OP1) involves cutting bars to the appropriate size which are then pressed (OP2) into the desired dimensions for the roller. Afterward, the rollers undergo a heat treatment process to enhance their hardness and durability. Following heat treatment, the rollers are grinded (OP3) and honed (OP4) to achieve precise dimensions. Figure 11 provides a visual representation of the production process, showing operation (OP) 1-4.

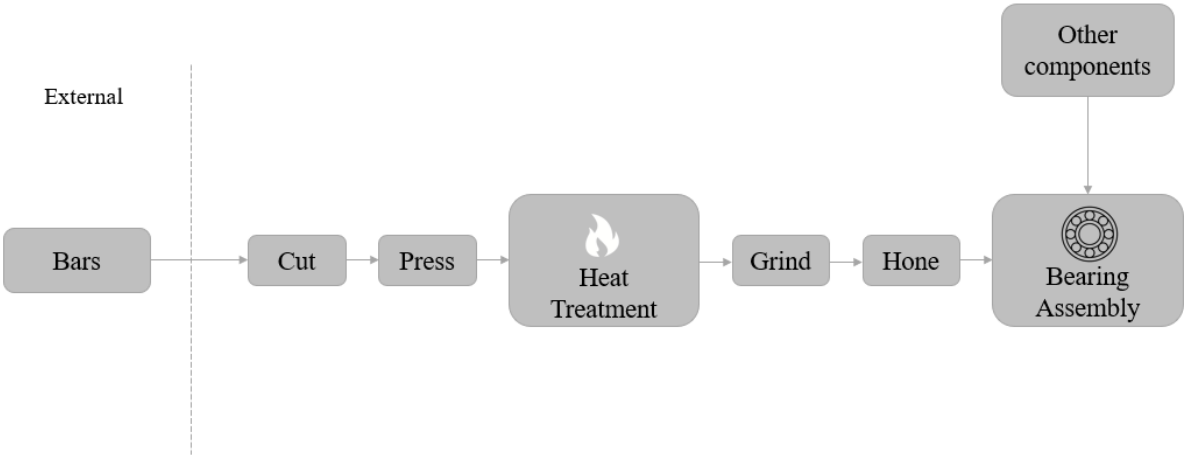


Figure 11 Production Process of Rollers

The rollers are measured in μ , where one μ is equal to 0.001 millimeters. The tolerance level of the rollers is indicated as (+) or (-) with a certain number, starting from 0 and going up/down in both directions with a 3 μ difference between them meaning that the bin indicated by a 0 includes dimensions from 0 to +3 μ , and the bin indicated by a +3 includes dimensions from +3 to +6 μ . For rollers in these production flows, the tolerance level goes from -6 to + 6.

SKF places great emphasis on the quality of its bearings, which is why the approved tolerance level for a roller is very small. If rollers in one bearing would have had rollers from different dimension spans i.e. bins, the quality of the roller would be lower, making it more prone to breakage and less able to withstand loads. This high amount of importance placed on quality, one of the five performance objectives presented by Slack and Brandon-Jones (2019), can be seen as an alignment with what the authors are saying about putting different amounts of emphasis on the objectives depending on the product line, thereby putting quality of the rollers high up on this list. Having this high amount of emphasis on quality is also in line with the sand-cone model presented by Slack and Lewis (2015) and Bellgran and Säfsten (2010), which describes that the performance objectives are cumulative, meaning that they build on each other, with quality acting as the foundation.

For this reason, before dispatching the rollers for assembly, they are carefully measured and sorted into bins. The reason for doing this is to have the same dimension of rollers in one bearing.

However, since quality as a performance objective serves according to Slack and Brandon-Jones (2019) not only as an external measurement but an internal one as well, the small dimension span of rollers can also be seen as a hindrance due to the fact that it is never possible to know beforehand exactly how many rollers that will be placed in one or another bin, only that it follows a normal distribution, risking having over- or understock depending on each situation. This can be connected to another performance objective, dependability, where Slack and Brandon-Jones (2019) say that the absence of it can influence operational costs and speed in a negative way, as seen when the number of rollers in one dimension span might not be sufficient to assemble a bearing, contributing to the need of producing more, thereby increasing operational costs and decreasing the speed.

The finished rollers are transported to the D-factory within the SKF industrial area using SKF internal trucks, using fossil-free fuel. Where full batches of rollers can be delivered in one truck.

As stated before, the production of rollers occurs in batches of generally over 10,000 units, as producing batches lower than that amount is seen as expensive. However, it is not certain that producing in smaller batches would lead to higher costs. The reason for this could be that overproduction means higher costs and more waste in production. According to Liker and Meier (2006), overproduction is the biggest cause of waste as it leads to other types of waste. When overproduction happens, excess inventory builds up in later stages of production, and these materials must wait until the next operation to be processed. This results in tied-up capital in the system and increases the lead time of production (Liker & Meier, 2006).

4.2 Current State Map

To accurately prepare the current state map, a comprehensive understanding of the shop floor dynamics and the collection of relevant data from diverse sources were essential. The approach to mapping the current state was based on the methodology recommended by Rother & Shook (2003). However, data collection encountered challenges in specific areas, hence, gemba walks were impractical and not possible at times. Therefore, data was alternatively obtained from SKF systems. Due to the long lead times in production, all data could not be collected on the same day. Additionally, valuable insights, particularly regarding information flows, were acquired through discussions with SKF Supply Chain Planners. These conversations were important in creating the current state map.

Two separate current state maps were developed for the RRY4-5 and DRQ2 production flows. The primary objective of creating separate maps for each flow was to facilitate a detailed analysis of the variations in material movement between them. For ease of reference and to provide a clear visual representation, a flow chart including both RRY4-5 and DRQ2 has been included in Appendix C.

As both production flows handle in total around 130 different roller variants i.e. dimensions, the most accurate way to capture the current situation was to take all of them into consideration, meaning all inventory levels consist of all types moving through that specific flow. The reason is that every roller is going through the same processes and is being processed by the same type of resources, aligned with the principle presented by Rother and Shook (2004) that the products that share resources are classified as a product family. However, because of considering all types, some mean values needed to be calculated and used as well.

The calculation of existing takt time is given in equation 1 below, where the data was gathered from the SKF database and by commonly agreeing with employees from the Supply Chain team on how to calculate it accurately. Customer demand per day varied between the two flows, therefore having two different takt times between the two current state maps. To determine the available production time for each day, historical data from 2023 was utilized. The overall available hours for the entire year were collected, and the mean value was calculated to estimate the average daily production time. Choosing what customer demand data to use was a more challenging task, because if looking historically, it was hard to separate the demand between the two production flows, and when looking at a specific day, the demand was shifting a lot. However, the chosen approach was therefore to use forecast data for the upcoming month to calculate the mean value per day.

$$TAKT\ time_{Existing} = \frac{Available\ working\ time\ per\ day}{Customer\ demand\ per\ day} \quad (1)$$

After gathering relevant data for the takt time, it was calculated for both production flows as shown in equations 2 and 3.

$$TAKT\ time_{RRY4-5} = \frac{18.3h}{12\ 791\ pcs} \approx 5s \quad (2)$$

$$TAKT\ time_{DRQ2} = \frac{18.3h}{8\ 468\ pcs} \approx 8s \quad (3)$$

The inventory levels shown in each VSM were captured through data extraction at a uniform moment across all storage and buffer locations. Initially, an analysis was necessary to identify and collect data on rollers passing through these distinct flows. Subsequently, the inventory at each stage, ranging from unprocessed bars to finished rollers, was examined to determine the duration each specific quantity remained at a location prior to its utilization. This analysis facilitated the calculation of the Days of Inventory (DOI), employing the method outlined in equation 4 below.

$$DOI = Inventory \times TAKT\ time \quad (4)$$

Upon the collection and verification of the data, the assembly of the two VSMS for the respective flows was completed. The VSM for RRY4-5 can be found in Figure 12 and for DRQ2 in Figure 13.

RRY4-5 Current State

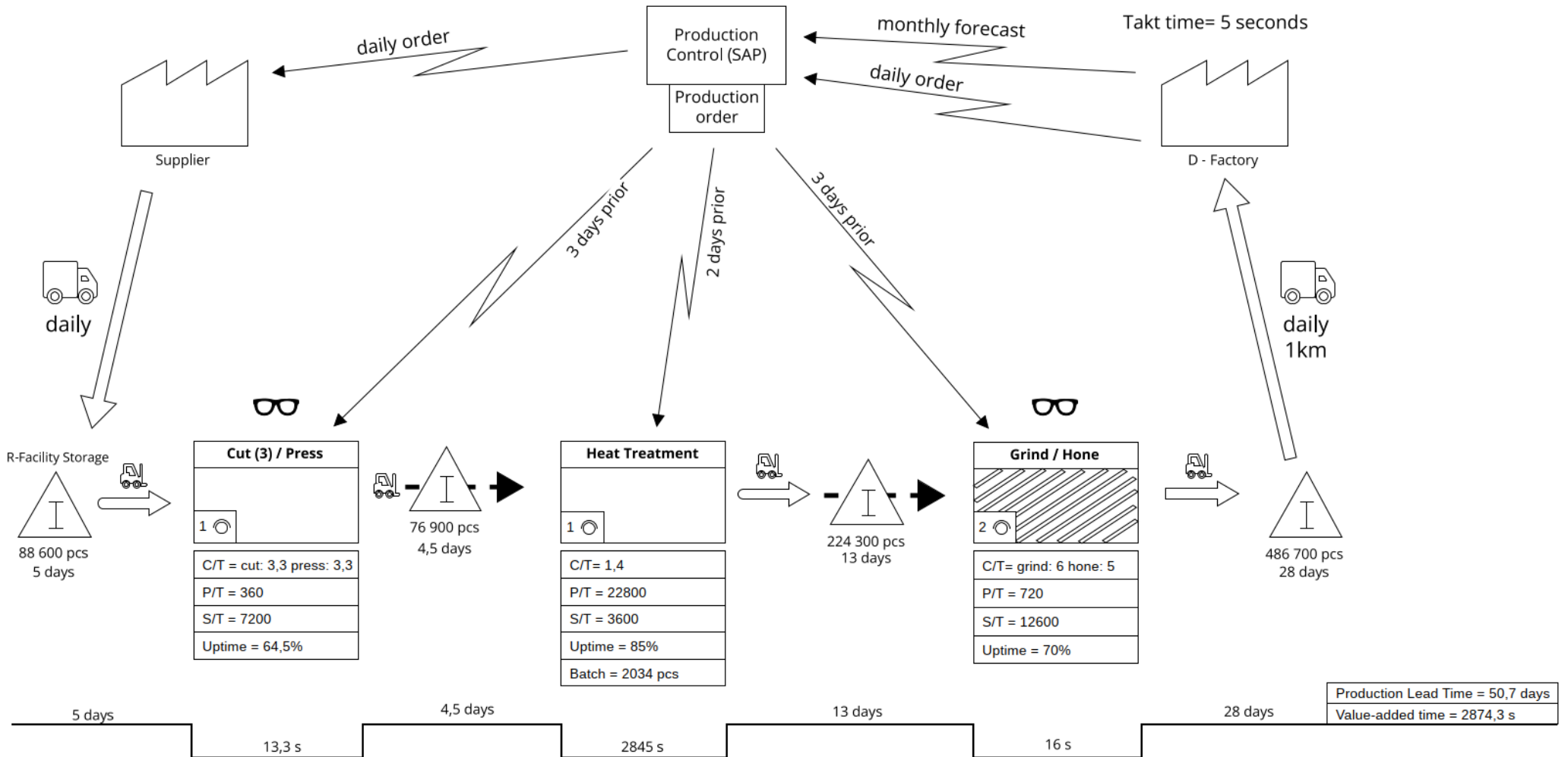


Figure 12 RRY4-5 Current State Map

DRQ2 Current State

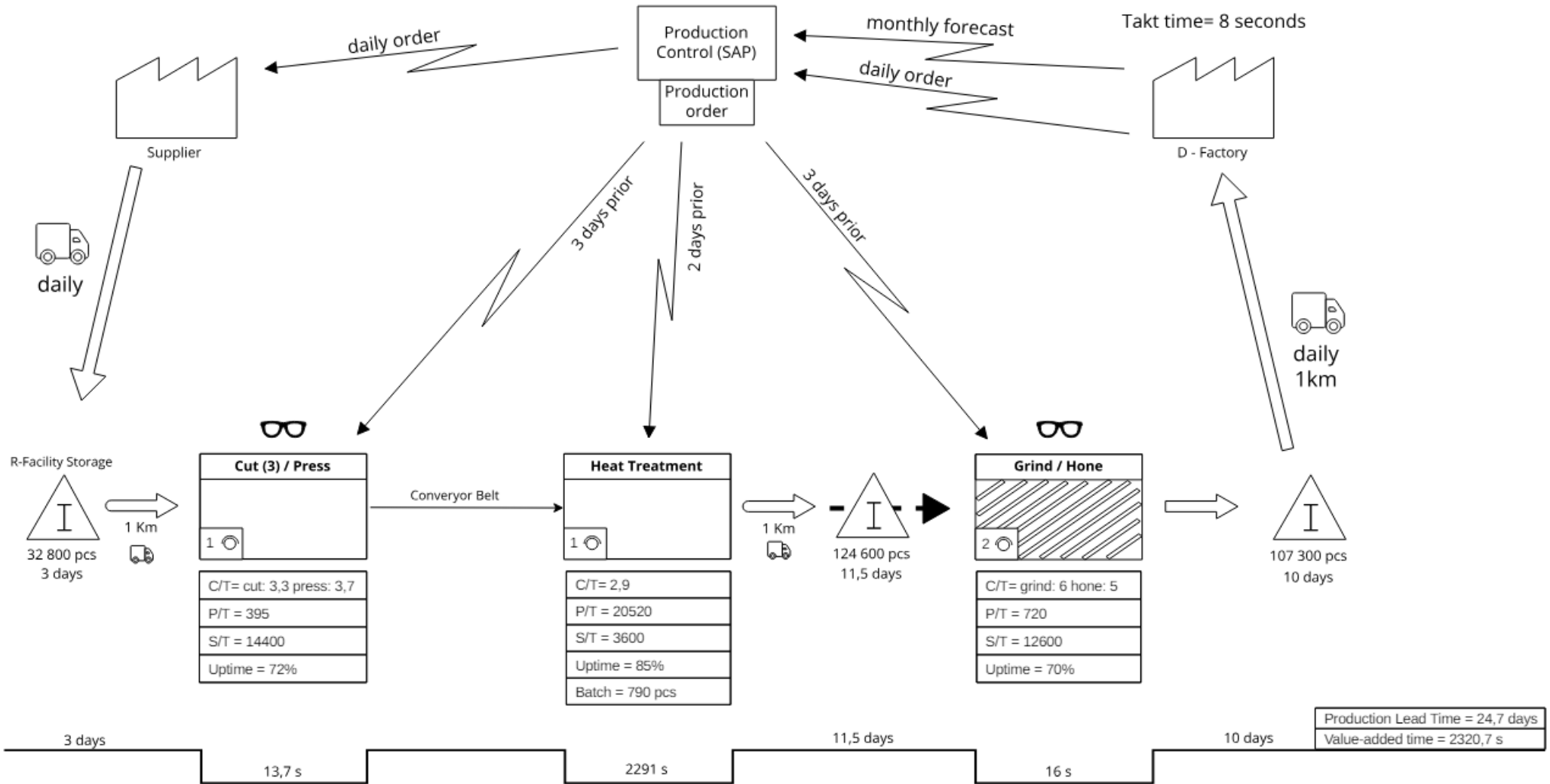


Figure 13 DRQ2 Current State Map

4.2.1 Production Flow

Cut and Press

The process initiates when bars are delivered to the storage area of the R-factory. Subsequently, these bars are moved to the section where cutting and pressing operations occur. The only distinction between the production flows of RRY4-5 and DRQ2 lies in the transportation distance; for DRQ2, bars must be transported one kilometer from the R-factory to the D-factory. Transport or movement is one of the eight sources of waste, meaning it is not seen as a value-adding activity however necessary it may be. Thus, reducing the need for transporting material between processes should be sought (Eaton, 2013; Liker & Meier, 2006). Additionally, this non-value-adding activity has a direct negative impact on speed, one of the performance objectives presented by Slack and Brandon-Jones (2019), contributing to longer lead time than necessary.

Both RRY4-5 and DRQ2 are equipped with three cutting machines and a single press where a conveyor belt connects the two operations. From a layout perspective only looking at these two operations, and according to Slack and Branon-Jones (2019), DRQ2 can be seen as a line layout since the resources are in alignment with the production process of the product. For RRY4-5, this setup is more in alignment with a cell layout since RRY4 and RRY5 are identical but separate. Within each cell, a line layout is used, in accordance with Slack and Brandon-Jones (2019) statement of having the possibility of having either a line layout or a functional layout within each cell.

Slight variances in their performance were noted. RRY4-5 demonstrates the same cycle time (C/T) for both cutting and pressing activities, attributed to the pressing machine's ability to align with the cutting machine's speed, with the potential for increasing its speed even more. Conversely, in DRQ2, the pressing machine's C/T is observed as longer compared to the cutting, creating a bottleneck in the press if looking only at these two operations.

It is important to note that the three cutting machines are used to reduce the C/T during the cutting operation. This results in a lower C/T, which means that the cutting process can have a C/T as low as, or even lower than, the pressing machine. Additionally, it is worth noting that these three cutting machines cannot be separated to work on different batches. This means that all three machines will always work together to cut bars for the same batch, which is the same for the cutting machines in RRY4-5 as well. One drawback of having a line layout is the lack of flexibility that comes with it (Slack & Brandon-Jones, 2019). This appears to be the case for both production flows due to the inability to separate cutting machines to work on different batches.

The total duration from when a roller is cut to when it is prepared for the heat treatment process, referred to as process time (P/T) in the VSM, shows noticeable differences between the two production flows, where the P/T in RRY4-5 is faster. Furthermore, RRY4-5 benefits from quicker setup time (S/T) compared to DRQ2, which can be due to the utilization of newer machinery and the lack of direct connection to the heat treatment operation. Having a quicker S/T, will directly impact the flexibility of the production flow, another performance objective presented by Slack and Brandon-Jones (2019), which can be seen as the ability to increase or decrease production. In RRY4-5, since having two identical but separated flows with a faster S/T and a disconnection to the heat treatment operation, flexibility is seen as higher than in DRQ2, having the possibility to faster change the type of roller being produced and address the shifts in demand in a better way.

Heat Treatment

Following the initial stages, for RRY4-5, the rollers are moved to a buffer location using forklifts, where they await entry into the heat treatment process, thereby resulting in a few days of inventory. Conversely, in DRQ2, rollers are moved directly to the heat treatment area through the conveyor belt system. Here, in terms of transportation seen as a waste, DRQ2 has an advantage since it utilizes a conveyor belt. It diminishes the waste “Motion”, meaning it avoids unnecessary movement by employees and makes transportation automatic (Liker & Meier, 2006). The line layout used in DRQ2 with the heat treatment included though comes with an increased disadvantage regarding flexibility and higher vulnerability when disruptions occur (Slack & Brandon-Jones, 2019).

The heat treatment furnace is a shared resource between RRY4 and RRY5. This means that both of those flows can utilize the heat treatment. Due to the extended processing time required for the heat treatment, it was deemed impractical to obtain the data through gemba walks. As a result, data was instead gathered from the SKF ERP system.

There are differences in performance between the two flows, mainly due to DRQ2 handling larger dimensions and smaller batches, alongside that the rollers arrive straight from the previous operations. This means that the larger size of the rollers undergoing heat treatment results in longer C/T for each roller. Additionally, the larger the size of the roller, the smaller the batches must be since larger rollers make up more space in the furnace. The calculated batch sizes shown in the VSMS were determined based on an average value extracted from the system.

Grind and Hone

After heat treatment, the rollers are moved to storage again, awaiting the final operations of grinding and honing. In the case of DRQ2, this entails transporting the rollers back to the R-factory, where they are stored alongside rollers from RRY4-5. Here, again, this means more waste in transportation and unnecessary movements between production processes (Liker & Meier, 2006). Despite the shared storage facility for rollers from both flows, traceability measures enable the identification of each roller's origin. This traceability facilitates the differentiation in inventory levels and DOI between the two flows.

Once requested, rollers enter the last process of grinding and honing which includes seven similar production lines, which is a shared process between the two production flows. After providing the finishing touches on the rollers, they are sent to a storage location where they will await to be transported by truck to the D-factory and the internal customers of bearing assembly.

This is the last transportation step before moving into final assembly. As for the rollers manufactured in DRQ2, this means that they have been moved three times between the two factories, leading to a total movement of three kilometers, contributing again to a negative impact on the performance objective of speed (Slack & Brandon-Jones, 2019). The same authors are implying that by increasing the speed i.e. shortening the time-to-market, uncertainties can be reduced and lower the risks connected to planning. Having this one-kilometer transportation between the two facilities directly impacts the time-to-market and planning perspective negatively, also contributing negatively to the ease of planning & execution.

Continuing the layout perspective, the final operations and shared process of grinding and honing can also be viewed in accordance with how Slack and Brandon-Jones (2019) define it as a cellular layout, with seven processes acting as cells where each cell follows a line layout. In conclusion, the two production flows follow not only one specific layout but two, which is according to Slack and Brandon-Jones (2019) a common way of using them, making it into a hybrid layout, trying to reach advantages from more than one layout type. When having a considerable variety of products, the cell layout gives a balance between costs and flexibility, and when looking at the line layout, it suits the manufacturing settings where mass production is used to facilitate reduced cost per unit (Slack & Brandon-Jones, 2019).

Production Lead Time and Value-Added Time

As for the total production lead time, it resulted in about 50 days for RRY4-5 and 24 days for DRQ2, calculated by adding the DOI with the P/T for every process. The total value-added time for the respective production flow is calculated by adding all the value-added time in the respective operation. For the first process, it is retrieved by adding the C/T in all three cutting machines with the C/T in the press. For heat treatment, the C/T is multiplied by the batch size. Lastly, for grinding and honing, the value-added time is calculated by adding the C/T for both grinding and honing. The result lands at around 2870 seconds (48 min) of value-added time for RRY4-5 and 2321 seconds (39 min) for DRQ2.

The target lead time for the rollers in both the RRY4-5 and DRQ2 is 35 days. This means that the RRY4-5 flow is 15 days late. The reason for this could be the overproduction of rollers since the VSM shows a large quantity of rollers in storage. As mentioned earlier, overproduction leads to more types of waste in the system, which affects the production lead time (Liker & Meier, 2006; Slack et al., 2013).

4.2.2 Information Flow

Regarding the information flow, both RRY4-5 and DRQ2 remain the same. The internal customers of bearing assembly have access to forecasts of their expected demand up to 1,5 years in advance. However, the supplier, i.e., roller production, only receives actual orders about a month prior to the delivery. Internal customers place monthly orders in their ERP system, and the system conducts MRP to calculate production orders. After this, supply chain planners review the orders, analyze the available stock, and identify any potential changes that need to be made. They then send the orders to external suppliers for raw materials i.e. bars. Only one supplier exists that supplies these production flows with bars.

As seen in the current state maps, production orders are initiated for each process a few days ahead of the actual production. After a process is completed, the planner generates an order for the next process, usually 2 to 3 days before production occurs. However, it was mentioned that there are cases where orders are made for both cutting/pressing and heat treatment simultaneously. The reason is that the production manager for heat treatment prefers to receive orders earlier so that they can plan production in advance.

Furthermore, within the roller production process, responsibilities for supply chain planning are not centralized under a single individual from start to finish. Specifically, in the RRY4-5 context, planning duties are divided among multiple planners: one is responsible for overseeing the cutting/pressing and heat treatment processes, while another planner focuses on the grinding/honing. Effective communication between the supply chain planners and the production manager is essential to ensure the timely production of the required number of rollers. However, this implies that the production manager needs to be aware of the customer demand.

For DRQ2, one supply chain planner manages the conveyor processes associated with cutting/pressing and heat treatment. The responsibility for planning the grinding/honing stages, however, is allocated to the same planner mentioned previously.

4.3 Identified Problem Areas

By reviewing the current state maps and in combination with the respondent's answers from the performed interviews as well as observations, several problem areas have emerged. Each area presents a challenge and opportunity to optimize the production system.

4.3.1 Takt Time

In developing the VSM, it became apparent that takt time was not a metric currently calculated and utilized in the control and planning of production for either of the two production flows. Although the takt time incorporated into the VSM was calculated with input from several employees, it is important to acknowledge that this measure lacks total precision.

Not knowing the correct takt time could potentially impact the optimization of the production process, as this is a key component for optimizing production flows and identifying areas for improvement (Rother & Shook, 2003). As explained by Chen et al., (2019), takt time can be used to control and manufacture at the pace that is necessary to fulfill customer demand, reducing overproduction which lowers the stock levels. From the interviews and observations when creating the current state map, it became apparent that stock is an ongoing issue in the roller production system.

However, takt time is mostly a concept used for production systems that use a pull system (Liker, 2004). As previously noted in chapter 4.1.1, the current production does not fully follow the pull-based principles but instead utilizes a mix of both push and pull, making this problem of not knowing the takt time further complicated.

4.3.2 Overproduction and Excess Inventory

Utilizing a mix of both push and pull in a way that the production system currently does, may also be one of the contributing factors to the observed overproduction within the system. For both production flows, RRY4-5 and DRQ2, the DOI preceding the grinding/honing operations, which, according to SKF employees, should be around three days, are significantly longer, indicating that production is completed earlier than necessary. However, the observed DOI does not, in a sense, only mean overproduction, it could also be because of the dimension of the buffers between the varying processes. This observation is similarly applicable to the finished goods for RRY4-5, where DOI should, again, according to SKF employees, be about 10 days.

The presence of excess inventory is a common problem observed in the VSM, closely associated with overproduction. This is particularly noticeable in the RRY4-5 production flow, where the total lead time is approximately 50 days, far exceeding the targeted lead time of around 35 days for roller production. Overproduction, being one of the major sources of waste, could be reduced by aligning the production more towards the actual customer demand, by use of takt time for example, and by using pull-based techniques such as a kanban system (Liker & Meier, 2006; Slack et al., 2013). This technique set a limit to the allowed WIP in the system, meaning that the overproduction could not go over a certain level (Chen et al., 2019; Chahal & Narwal, 2017). This would lead to lower stock in the whole production system, which is seen as something sought after by the interviewed SKF employees.

Moreover, one main contributor to overproduction according to Chiarini (2012) is the implementation of oversized economic batch sizes. As mentioned previously, current production orders are usually limited to batches over 10,000 units as it is not seen as economically sound to manufacture under that limit.

Excess inventory, often derived from overproduction, leads to an increased need for storage and longer lead times as well as increased costs due to transportation, tied-up capital, obsolescence, and damaged goods (Liker & Meier, 2006). An increase in costs means that the performance objective cost is affected negatively. As explained by Slack & Brandon-Jones (2019), cost plays a critical role in any company as it directly affects their profit margins. Additionally, without having a large inventory in the warehouse, it is possible to deliver high-quality to customers at a lower cost (Liker & Meier, 2006). For SKF, it is crucial to evaluate the implications of excess inventory, given its numerous drawbacks, which is why stock is included as a KPI.

Additionally, according to Rother and Shook (2003) and Liker and Meier (2006), excess inventory is a significant cause of extended lead times within a production system. Furthermore, Hopp et al. (1990) assert that shorter lead times result in reduced WIP, which in turn lowers the requirement for storage space. As seen in the current state maps, the large amount of storage is pointing towards overproduction and excess inventory in the production system.

4.3.3 Transport

The one-kilometer distance between the D- and R-factory represents an inefficient transfer of goods, as highlighted in the description of the production flow in the VSMs under 4.2.1, leading to extended production lead times and complicating the planning process. Transport is considered a waste according to Liker and Meier (2006) as it contributes to longer lead times and more unnecessary time spent by SKF personnel to transport the goods.

The overall factory layout affects the need for transportation, the longer distance between processes within a production flow increases the time spent to move the products between processes (Slack et al., 2013). Considering that rollers are being moved three times with a total of three kilometers, this is seen as a waste since it contributes to longer lead times and more material movement.

According to Dennis (2007), transport waste often originates from poor factory layouts. For example, if a production flow for roller manufacturing were to have a cellular layout, then all necessary processes to produce a finished roller would be close to each other, this means that there is less distance between processes which, in turn, would reduce the lead time for roller manufacturing (Slack et al., 2013). Moreover, this would increase the performance on the performance objective speed, highlighted as crucial for reducing inventory according to Slack and Brandon-Jones (2019). The reason why speed is important to reduce inventory is that the journey of the material throughout the production system is far greater than the processes, meaning that it spends most of its time in stock. So, the longer time products take to move through a process, the more time they will be waiting and the higher the inventory will be (Slack & Brandon-Jones, 2019).

The authors further highlight that speed can reduce the risks in operations since the faster the lead time is the later forecasting can be left. Thus, a higher performance in speed means that it is more likely that the number and types of products that are being manufactured eventually will be needed (Slack et al., 2013). Furthermore, the KPI of ease of planning & execution is seen as important to SKF personnel, and placing processes in closer proximity could improve that KPI.

Right now, it can be considered that a functional layout is overall being used for the production system since similar processes are in close proximity and when that process is finished the roller is either transported into storage or transported to a different process located elsewhere (Slack et al., 2013).

As mentioned by Chiarini (2012), excessive inventories are one of the main contributors to an increase in transportation since they cause a need for the transportation of products from one warehouse or storage to another. Given the large number of items in storage, visualized in the current state maps, it goes to show that additional transportation is necessary between storage, buffers, and processes since Chiarini (2012) and Liker and Meier (2006) mention that it is the case when there is excessive inventory in a production system.

4.3.4 Constraints

When observing the current state maps and looking at DRQ2 flow, the cycle times across all operations are shorter than the takt time, theoretically indicating that meeting customer demand should not present a problem. However, the situation differs for RRY4-5, where the cycle time for grinding/honing exceeds the takt time, pinpointing the grinding/honing operation as the bottleneck. This is one of the reasons that accounts for the strategic placement of the storage location prior to this operation. This is in line with what Goldratt and Cox (1992) say about placing the buffer location before the drum i.e. the bottleneck, that sets the pace of the production.

However, a highlighted challenge by interviewees, is that the cycle times in the heat treatment operations vary a lot, creating constraints that impact the efficiency of the production system. Smaller rollers, which undergo a quicker cycle time in heat treatment, shift the constraint to an earlier stage, the cutting operation. Conversely, larger rollers, which take longer time in heat treatment, position the constraint within the heat treatment process itself. This is something that is not actively managed, and by having the constraints' location change from time to time depending on the roller variant produced but not changing the location of the buffer, it contradicts the drum-buffer-rope concept presented by Goldratt and Cox (1992).

A bottleneck can be seen as a form of constraint, which is characterized as any factor that negatively impacts and restricts the efficiency of a system. However, the change of location of the constraint is not an issue itself but rather the opposite, since the principle of TOC, presented by Jonsson and Mattson (2009), is to continuously evaluate the constraint so that it can be improved, thereby having the constraint to be changed to another operation.

Moreover, as described by SKF personnel, it necessitates communication between the production manager for the heat treatment and the supply chain planners. This makes the planning of roller manufacturing more complex since the heat treatment is a complex process to plan and thereby the production manager has to make the final call on what and when to produce, evidently impacting the ease of planning & execution KPI.

4.3.5 Personal Judgement Decisions

The absence of a standardized framework for decision-making in certain aspects of production planning introduces the possibility of variability and inefficiency. In the case of SKF, decision-making within planning production often relies on the expertise and personal judgment of the individual employees involved in planning. An example of this, explained by an SKF employee, is the case when a supply chain planner is planning the heat treatment process. The planner does not have sufficient guidance from the system to plan that process by only relying on the system. Thus, a production manager for the heat treatment is contacted, and that individual must make individual decisions for the planning of the heat treatment.

This dependence becomes particularly problematic with personnel changes, leading to inconsistency in production planning. As mentioned earlier, planning the production system can be challenging when the person with the required expertise is unavailable. Relying solely on specific individuals is not an ideal situation as expressed by an SKF employee.

Consequently, achieving a high score on the ease of planning & execution KPI becomes more difficult when depending on individuals. Furthermore, when depending on individuals to plan the roller manufacturing, and the person with the required expertise is out of the office, it could affect the dependability performance objective. Dependability is expressed as a performance objective that affects quality and speed in an organization, performing poorly could lead to more operational costs and not meeting customers' expectations (Slack & Brandon-Jones, 2019). Not keeping delivery promises given to customers could lead to customers looking to buy elsewhere (Slack & Lewis, 2015). According to an interviewee, this problem could be reduced or eliminated if the system could support decision-making at every level for the supply chain planner.

4.3.6 System Support

A highlighted issue contributing to the problem of personal judgment decisions is the insufficiency of the data systems currently in use for some planning activities. These systems do not provide the functionalities necessary for optimal decision-making, forcing employees to rely on their competence and experience to make decisions. Introducing higher flexibility into the production system without upgrading these systems could further complicate planning processes, placing even more emphasis on individual judgment and decisions. This means that system support is closely linked to ease of planning & execution since it affects how supply chain planners conduct their day-to-day tasks.

For the supply chain planners to be able to be more effective, according to an interviewee, when utilizing a push system, a reliable and advanced system should support the planners to make decisions solely based on the data provided by the system. This means, not necessitating any objective reasoning, connected to previous issues on personal judgment decisions. The system should have enough information to be able to provide reliable data to the supply chain planners, making it simpler for the planners to plan the production.

According to Slack and Lewis (2015), a well-integrated ERP system can help planners in their decision-making, providing information on when, where, and who should do certain activities as well as how much capacity is needed. Furthermore, the system will reduce the need for manual planning tasks since those tasks can take place within the integrated system (Slack & Lewis, 2015). Moreover, all necessary data should be provided to relevant SKF personnel, such as production managers, and within a convenient timeslot, to avoid discrepancy and confusion on what to manufacture.

However, in contrast, if a pull system were to be implemented, such an advanced system would not be necessary, and the planning process could be more simplistic, both system-wise and operational. This includes both production scenarios although the Flexible Flow would benefit more from a more simplistic system like pull.

5. Production Scenarios

The objective of this chapter is to address and answer RQ3 and RQ4. To achieve this, a comparison between the two scenarios and how they manage the identified problem areas is carried out to answer RQ3. Further, the MCDA, based on evaluating the scenarios towards the KPIs of the project, is presented. Finally, based on the comparison and the results from the MCDA, the answer to RQ4 is presented.

5.1 Main Differences between Simplified Flow and Flexible Flow

This section outlines the main differences between the two production scenarios, Simplified Flow and Flexible Flow. Each scenario represents a distinct approach to managing production flows and resources, aiming to optimize various aspects of the production system. In Simplified Flow, a streamlined, standardized production path designed to enhance predictability and flow efficiency is explored. Conversely, Flexible Flow emphasizes flexibility and resource efficiency, accommodating disruptions in production and reducing dependencies on fixed production paths. Flexibility in the Flexible Flow is as previously mentioned, when a roller can be manufactured in every production flow and take all possible routes, meaning that one variant of roller dimension is not being processed in the same flow and machines each time.

5.1.1 Simplified Flow

Flow Efficiency

In the Simplified Flow, emphasis is placed on enhancing flow efficiency and adopting a comprehensive approach to managing production resources and their flow. According to Bellgran and Säfsten (2010), flow pertains to the seamless progression between activities, aimed at ensuring precise delivery of each component to the designated recipient, in the appropriate quantity and at the correct time. Rollers in this Simplified Flow are produced through a predetermined flow, utilizing the same resources each time that specific roller variant is to be manufactured. This improves flow efficiency and reduces queues in the production system since rollers are allocated to certain resources that are ready to be used whenever a customer demands that roller.

However, this approach can result in excess capacity in the system's resources, as not all types of rollers are continuously in demand from customers. This may lead to high flow efficiency but low resource efficiency, as described by Modig and Åhlström (2012) as "the efficient ocean." To meet customer demand, excess capacity in resources is often maintained, even though the resources are not being used to their fullest potential (Modig & Åhlström, 2012). Excess capacity may increase roller costs, but overemphasizing resource utilization may lead to higher waiting, inventory, and operator costs (Modig & Åhlström, 2012).

As previously mentioned, the production of rollers is only considered profitable in quantities exceeding 10,000 units. Improving flow efficiency would allow rollers to "flow" through the production system in a more efficient manner, enabling shorter lead times during production, and potentially eliminating the need for large batch sizes. Given the shorter lead times, roller manufacturing could be based on what is needed to be produced. This approach would yield numerous benefits, including a significant reduction in stock levels. As explained by Hopp et al. (1990), having a shorter lead time reduces the amount of WIP, which enables a reduction in stock levels.

Line Layout

Slack and Brandon-Jones (2019) explain that a line layout uses a fixed production path for each product and follows a specific sequence. This aligns with Simplified Flow, as all rollers will have a fixed, predetermined, production path.

Slack and Brandon-Jones (2019) further explain that line layout organizes resources in alignment with the production process of the products. This means that all resources that are necessary to manufacture a complete roller would be organized in sequence, not necessitating any material movement between the processes. This reduces waste known as motion and transport (Liker & Meier, 2006).

However, in the current situation, transportation is necessary between the R- and D-factory and between some of the processes in the two flows of RRY4-5 and DRQ2. So, even though the line layout is not a direct translation of the Simplified Flow scenario due to these disconnections between processes, the principle is similar with having the same dimension of rollers always taking the same production path.

Additionally, as mentioned by Liker and Meier (2006), a continuous flow (one-piece flow), that physically links process steps, would have no inventory between processes, evidently reducing stock levels in the production system. To achieve this, a reduction of batch sizes is necessary to move toward continuous flow (Liker & Meier, 2006). However, for roller production, the resources are not all physically aligned, rather the principle of a line-based layout can be incorporated into the production system. Thus, a fully continuous flow, as described by Liker and Meier (2006), is not currently feasible in roller production. But as mentioned, the first step toward continuous flow is to reduce the batch sizes.

A drawback to utilizing the line layout entails lower flexibility in the system, leading to higher vulnerability towards disruptions in production and changes in customer demand (Slack & Brandon-Jones, 2019). However, this is opposed by Liker (2004), who says that by having a line layout that accommodates having low stock levels and WIP, lead times will be reduced and, real flexibility, the ability to adapt to variations in production and demand, can be achieved. Applying this to the Simplified Flow would then facilitate a production that only produces rollers that are needed from the internal customer.

5.1.2 Flexible Flow

Resource Efficiency

According to Modig and Åhlström (2012), when organizations prioritize resource efficiency, the aim is to utilize their resources to the fullest in each process. This approach can lead to cost savings in production, but it can also result in waste such as waiting times, longer lead time as well as high inventories. In this context, Flexible Flow, the flexible flow, resembles and emphasizes resource efficiency by maximizing machine utilization through a flexible production system, not constraining the different roller dimensions to one specific resource and flow.

During SKF personnel interviews, the importance of flexible production systems was emphasized to handle disruptions caused by resource breakdowns. By utilizing the flexibility of being able to manufacture rollers in other machines when the intended machine has a breakdown, it is possible to continue manufacturing instead of waiting for the broken machine to be fixed. However, this entails that overcapacity is necessary in the system as well since an alternative resource is ready to process the rollers that were intended to be produced elsewhere.

The interviewees also noted that having too many fixed route flows can hinder the system's ability to handle disruptions, resulting in lower capacity utilization. Therefore, a more flexible production system can lead to higher capacity utilization by effectively managing disruptions.

A flexible production system also enables a swift response to unexpected shifts in customer demand (Slack & Brandon-Jones, 2019). The authors also imply that with enhanced flexibility it is possible to improve operational efficiency as well as customer satisfaction. Higher customer satisfaction in this regard implies that a roller can be provided in time to the internal customers, resulting in a higher availability KPI. For instance, if there is a higher demand for rollers than anticipated, the flexible system can manufacture them in various flows to meet the customer's needs. However, if taking the standpoint from Liker (2004) and, to enable a swift response to the shift in demand which is according to the author referred to as "real flexibility", low lead time is necessary to be able to reach this kind of flexibility. Therefore, by having the Flexible Flow which prioritizes resource efficiency and thereby has higher inventories and longer lead times, the ability to meet variations in demand can be considered to be lower.

Further, the interviewees were concerned that the Flexible Flow can also cause instability in the production system, making it challenging to keep track of everything given the possibility of making late changes in the system.

If Flexible Flow were implemented, it would significantly increase the complexity of the production system. As a result, the supply chain planners would need to engage in a more complex and time-consuming planning process, given that the process and system are more complex. Slack and Lewis (2015) suggest that an ERP system could be utilized to manage these operations.

During interviews with SKF employees, it was noted that a highly advanced and integrated system would be necessary to manage a complex system like Flexible Flow, which is not yet in place at SKF. Therefore, Flexible Flow will underperform on the ease of planning KPI if no advanced system is there to support the decision-making in the push system.

Functional Layout

According to Bellgran and Säfsten (2010), a functional layout has the potential to optimize capacity utilization by organizing similar resources in close proximity to each other. This enhances flexibility, which allows for more product variants and adaptation while maintaining resilience towards disruptions in the production system. This aligns with Flexible Flow's focus on flexibility, capacity utilization, and adaptability in production.

To maintain flexibility within SKF's production system, and the ability to reroute rollers, it is important to be able to accommodate roller variations across similar resources. An interviewee has noted that this could result in increased costs for equipment, as each resource may require additional equipment to produce a large variety of rollers. Furthermore, Bellgran and Säfsten (2010) emphasize that the complexity of a functional layout can result in extended lead times and complicated production planning, leading to delays and queues for transportation between processes, showcasing a risk that Flexible Flow would result in a more complex planning process.

As previously mentioned, rollers are currently manufactured in batches of over 10,000 units. This poses a challenge, according to interviewees, as it often results in excess stock in the production system. For instance, if an order for 3,000 rollers is placed, the planner may add 7,000 more to produce a full batch. The rationale behind this approach is that the supply chain planners anticipate future demand for that type of roller in the coming month. Considering the large batch sizes currently used in the production system, combined with the functional layout could, as explained by Slack and Brandon-Jones (2019), mean high WIP or customer queuing. Leading to high inventories and longer lead times in the production system (Hopp et al., 1990). Moreover, when having large batch sizes in a functional layout, products are moved in full batches between processes, further contributing to high WIP (Slack & Brandon-Jones, 2019). Thus, this increases the need to reduce the batch sizes for SKF roller production.

Functional layout is an ideal production system for environments with a wide range of products produced in small batches as they can take their own route (Zandin, 2001). However, upon examining the current production of rollers, it is clear that while all rollers are processed using the same type of resources, not every resource is capable of processing all roller dimensions. Consequently, the product range is narrower than it may appear, despite the existence of 130 different rollers.

Furthermore, setup time and WIP tend to be high in a functional layout, and the lead time in this system mainly occurs between the processes, with actual machining time constituting only a small percentage of the overall lead time (Zandin, 2001). Having longer setup times and higher WIP results in a need for higher stocks and thereby longer lead times. This makes it harder to reduce the batch sizes and to produce only what is demanded from the internal customers.

5.2 Management of Identified Problem Areas in Respective Production Scenarios

The problem areas identified in section 4.3 concerning the current production system are of great importance in determining the most suitable scenario for SKF's roller production. Consequently, this section will present the outcomes of how each flow addresses these issues individually.

5.2.1 Takt time

The identification of various issues revealed that takt time, a crucial metric for optimizing production flows, is not currently implemented in the control and planning of SKF's production systems. This oversight leads to challenges in accurately aligning the production pace of rollers with customer demand from bearing assembly, contributing to persistent stock issues within the roller production system. As the current production system utilizes aspects from both push and pull, this issue is only more complicated.

Simplified Flow, with its structured and consistent routing for specific dimensions of rollers, facilitates a more predictable production flow. This predictability can be advantageous in many aspects, but not regarding the issue related to takt time, at least not if trying to use it as a concept of controlling the flow. As Liker (2004) says, takt time is a concept mainly utilized in pull-based production systems and when flow efficiency is considered a problem. Therefore, the line layout described by Slack and Brandon-Jones (2019), which Simplified Flow resembles, and which puts high effort into flow efficiency, makes the issue of not knowing the takt time less important.

In contrast, Flexible Flow emphasizes resource utilization with its ability for rollers to take whichever path possible in the production system, resulting in less focus on flow efficiency. This reduced emphasis on flow efficiency is then in line with Liker (2004) and his ideas of utilizing takt time on a production system where flow is considered a problem. With that said, calculating a correct takt time in the Flexible Flow Scenario might not be an easy task.

Liker (2004) highlights the primary challenge associated with utilizing takt time: accurately determining customer demand. This task becomes particularly challenging in production environments characterized by diverse products and fluctuating demand. To address this challenge, Liker (2004) underscores the importance of understanding the consequences of deviating from takt time, with one example of having standardized cycle times in production enabling easy adjustment of production time to accommodate demand variations. As mentioned by Liker and Meier (2006), a reduction in batch sizes is necessary to achieve a continuous and line-based flow.

However, the issue arises for the Flexible Flow Scenario, resembling the functional layout described by Slack and Brandon-Jones (2019), and production systems in general, where cycle times are not standardized. This lack of standardization is especially evident in heat treatment operations, where cycle times vary significantly depending on the roller dimensions produced.

5.2.2 Overproduction and Excess Inventory

Overproduction and excess inventory issues in the production flows of RRY4-5 and DRQ2 are major issues in the production system, that result in early production completion and extended DOI. This imbalance leads to increased lead times and surplus inventory, which not only incur additional storage and capital costs but also negatively impact operational efficiency. Overproduction can be caused by the push method of planning, wherein the MRP system pushes orders for production more than what is needed. This results in excess inventory that is often wasted, leading to increased costs. To avoid this overproduction, a pull system can be used instead. For example, kanban cards can be utilized to manufacture to lower WIP (Liker & Meier, 2006).

In Simplified Flow with the fixed routing system, the predictability of the production flow can have both benefits and limitations when it comes to addressing overproduction and excess inventory. Liker and Meier (2006) and Chen et al. (2019) mention that implementing pull-based systems, such as kanban or two-bin systems, is proven to regulate WIP by triggering production based on actual demand. Hopp et al. (1990) mention that reducing WIP reduces stock levels in the production system. According to an interviewee, Simplified Flow's material flow, which is direct and predictable, facilitates easier stock management and minimizes the risk of material shortages. The interviewee further mentioned that the predictability of Simplified Flow allows for a more controlled implementation of WIP caps, ensuring that production does not exceed set limits. Moreover, an interviewee also mentioned that for Simplified Flow, the material flow

will be more linear and easier to comprehend, which facilitates both the physical and digital management of material.

Moreover, Chiarini (2012) highlights that a common reason for overproduction is the implementation of oversized economic batch sizes. As previously mentioned, the batch size is currently advised to be over 10,000 rollers by SKF. The Simplified Flow supports the implementation of pull-based systems, given its predictability and simplicity. Thus, by utilizing pull, manufacturing could take place based on what the customer needs and enable the possibility of having smaller quantities of each roller in stock (Liker & Meier, 2006). This entails that it is necessary to be able to manufacture in smaller batches.

However, it should be noted that when reducing the batch sizes, it might become more costly to manufacture the rollers from a resource utilization perspective. Although, it could lead to lower costs from overproduction and excess inventory. However, according to Liker and Meier (2006), the waste “overproduction” is one of the worst wastes which brings other wastes into the production system.

Flexible Flow is characterized by a flexible routing system which can increase the complexity of managing overproduction and excess inventory, given the focus on resource efficiency and higher inventory levels (Modig & Åhlström, 2012). As mentioned earlier, the implementation of a pull system can effectively minimize overproduction and excess inventory (Liker & Meier, 2006). Considering the complex nature of Flexible Flow and the simplicity of pull, it is probable that the potential benefits of utilizing pull in this production scenario would be greater and more significant when compared to Simplified Flow.

However, adaptability may help maintain optimal inventory levels by reducing batch sizes, according to an interviewee. Furthermore, Zandin (2001), mentions that a functional layout can produce a large variety of products in smaller batches. This might reduce the highlighted issue regarding the batch size of 10,000 units, where oversized batch sizes are seen as a normal cause of overproduction (Chiarini, 2012).

5.2.3 Transport

The transport inefficiencies in the current production system, highlighted by the one-kilometer distance between the D- and R-factories, result in increased lead times and complexities in the planning process, where Liker and Meier (2006) identify transport as a source of waste.

In Simplified Flow, the transport problem area is seen as a challenge due to the rigidity of the production layout. The 1-kilometer distance between the R and D factory shows inefficiencies since Liker and Meier (2006) mention that transport contributes to longer lead times and increased non-value-added activities. However, the simplicity and predictability of Simplified Flow could enhance the possibilities of improvements in logistics and layout optimization. A benefit of Simplified Flow in this regard is the ability to establish set paths, enabling dedicated shuttle routes and thus making transportation more efficient.

Dennis (2007) mentions that poor layout facilities are one of the main contributors to transport waste. Thus, changing the layout is fundamental in reducing transportation. Due to the functional layout currently used, this problem area will likely persist unless that change is made. Slack et al. (2013) mention that utilizing a cellular layout, where all necessary processes to produce a finished roller are closer together, could reduce the transport waste since there is no need to transport from R to D-factory and vice versa. Moreover, Chiarini (2012) explains that when reducing inventory levels, it is also possible that transportation needs are reduced as well. As explained in section 5.3.2, Simplified Flow can reduce inventory levels by potentially utilizing a pull-based system.

In contrast, in Flexible Flow, there are different possibilities and challenges for managing transport waste. A flexible production system, utilizing a functional layout, would mean that transport would always be necessary to produce a finished roller. Moreover, in this production scenario, rollers could be moved to different destinations as needed, potentially increasing transportation between processes. As previously noted, Dennis (2007) identifies the facility layout as the primary contributor to transportation issues. Thus, without changing the layout of the flexible, to perhaps a cellular or line layout within a single facility, it will not remove the transportation needs fully.

Therefore, both Simplified Flow and Flexible Flow have the opportunity to optimize transportation, mostly where Simplified Flow reduces the distance between processes. However, without changing the layout of the facilities, and incorporating all necessary processes to finish a roller in the D-factory, reducing the need for transportation between the R and D-factory will not be possible. As mentioned by Slack and Brandon-Jones (2019), the performance objective speed is important for a production system because of the various benefits it provides, e.g. reduced risks and inventory. By reducing transportation, it is possible to increase the performance in speed (Slack & Brandon-Jones, 2019).

5.2.4 Constraints

Having varying cycle times, sometimes even exceeding the calculated takt time, and not actively working with the constraints in the system, is the next issue at hand.

The method of Simplified Flow by having a more structured approach and predictable production paths, facilitates a good management of constraints. The consistency in having each roller variant follow a consistent route through the production system aids in pinpointing where constraints occur due to when that happens it will be seen directly. This will better facilitate the first of five steps presented by Jonsson and Mattsson (2009) of aligning production and material flow with customer demands, which is to identify the constraint. It would also facilitate working with reducing the varying cycle times, mostly in heat treatment, due to the predetermined paths for the rollers, making the dimensions of rollers designated for each heat treatment operation vary less and therefore having less difference in cycle times. However, it should be noted that in the two flows of RRY4-5 and DRQ2, there is only one heat treatment operation in the respective flow. If having the option of utilizing more heat treatment operations, this issue would be further minimized.

Flexible Flow, with its focus on utilizing the resources as much as possible, would instead risk increasing the issue regarding varying cycle times in the heat treatment operation. Having all dimensions of rollers be processed in every heat treatment operation, the difference in the size of the rollers will be as large as possible, which will mean that the difference in cycle times will not be improved. While the increased flexibility in the setup of Flexible Flow might lead to higher resource utilization, as highlighted by Slack and Brandon-Jones (2019), the variability in process paths for the rollers and having large differences in cycle times in the heat treatment operations, could lead to inconsistencies in lead times and complicate the communication between production personnel and supply chain planners. From the perspective of Jonsson and Mattson (2009) who say that a constraint is every factory that negatively impacts and restricts the efficiency of the production system, this can be seen as a constraint that could prove to be difficult to handle.

5.2.5 Personal Judgement Decisions

The reliance on the personal judgment and expertise of individual employees creates variability and inefficiency. This situation hinders consistency in production planning which negatively impacts KPIs like ease of planning & execution and jeopardizes the performance objective of dependability in meeting customer expectations.

As mentioned previously, a current issue of individual decisions being made is when planning the heat treatment process. The current production manager is the one who plans the heat treatment process.

The Simplified Flow offers a structured and predictable production system that can be beneficial for standardizing decision-making processes. By having a predefined path for each product or material flow, as mentioned by an interviewee, the dependency on individual judgment can be minimized, as critical decisions about the planning and processing of material are largely predetermined. The interviewee further mentioned that having a simpler production system could lead to an easier planning process for the supply chain planners.

Moreover, this leads to a decision-making process that could be conducted based on suggestions solely from the system, simplifying and minimizing the time needed for the planning process for supply chain planners. The interviewee believes in a simple planning process, where the supply chain planner can monitor the suggestions provided by the system. It was also mentioned that in the future, the planning process might be conducted only based on system recommendations. SKF's ERP system could provide detailed planning and operations instructions to aid in decision-making for the supply chain planners, decreasing the need for manual tasks in the decision-making process, highlighted by Slack and Lewis (2015) as one of the advantages of a well-integrated ERP system.

In contrast, an interviewee mentioned that the Flexible Flow would require a more dynamic decision-making process. The reason was that changes could be made during several stages in the production process, where different individuals would need to make decisions instead of just relying on the system to make them. Flexible Flow offers the possibility to make adjustments and optimizations in real-time, which, while beneficial in handling variability in production demands, also increases the reliance on the individual judgment of planners as well as operators. Thus, to reduce the problem area of personal judgment decisions, according to an interviewee, it requires an advanced system that can take everything into account when it comes to decision-making in a complex and flexible system.

Further mentioned by an SKF employee, that in a complex system like Flexible Flow, supply chain planners would constantly need to look for optimizations in the planning process, and the interviewee believes in a simpler planning process rather than a complex one. However, Slack and Lewis (2015) mention that an advanced ERP system that has been well-integrated can be utilized to support decision-making by offering data-driven insights and recommendations in the production process. This correlates with what was mentioned by an interviewee, that planning production in a push system, combined with the Flexible Flow, requires a more advanced system than what is currently in place.

However, another take on this is that the flexible flow should utilize a more simple planning and decision-making process, such as a pull system. Instead, it should be the Simple Flow that utilizes a more advanced and dynamic decision-making process because of its simple production system. This way, the Simple Flow could be planned in more detail, pinpointing exactly how and when rollers should be manufactured.

To conclude, personal decision-making can be reduced by utilizing an ERP system, as described by Slack and Lewis (2015). Furthermore, Simplified Flow's predetermined flow supports and simplifies the planning process whilst Flexible Flow's complex production system is more demanding on the ERP system if a push method is used, thus, requiring a more advanced system for decision-making. In contrast, if a pull system were to be used, it could benefit and simplify the planning process for both scenarios. However, the Flexible Flow, with its complex nature, could gain the most benefits from a pull system whilst the Simplified Flow could gain more advantages when given the possibility to make detailed and dynamic planning decisions. (Liker and Meier, 2006).

5.2.6 System Support

The system support in current production is limited by its lack of functionalities necessary for optimal decision-making, leading to an overreliance on employee judgment and experience in planning activities. This insufficiency hinders effective planning and decision-making processes, underscoring the need for a more integrated and reliable system that supports supply chain planners by providing comprehensive, timely, and accurate data, thereby reducing the reliance on manual and subjective decision-making, connected to previous issues.

In Simplified Flow, the ERP system can be used to support the system and reduce the need for personal judgment. As discussed with an SKF employee, a simple production system could enable decision-making based solely on suggestions from the ERP system. The SKF personnel would need education in the system to utilize it correctly and to trust it, according to an interviewee. As further mentioned, a more simplistic system would require less configuration in the system to be able to get precise suggestions and recommendations for the supply chain planners.

According to Slack and Lewis (2015), a comprehensive ERP system can provide detailed guidance on production activities, scheduling, and capacity management. The ERP system can ensure that all the necessary data are available to the production managers and planners in a timely and accurate manner, minimizing discrepancies and confusion in the manufacturing process. Therefore, while the system can improve efficiency and reduce the need for manual planning tasks, a downside mentioned by an interviewee is that it may not fully compensate for the inflexibility of fixed production routes without some enhancements to allow for responsive adjustments in planning for the Simplified Flow.

In Flexible Flow, the need for an advanced ERP system becomes even more critical according to multiple interviewees. The dynamic nature of Flexible Flow requires a system that not only provides comprehensive data but also supports decision-making and adaptability in the production planning process. This would enable Flexible Flow to maximize its potential, allowing for real-time adjustments in production routing based on current conditions and demands, thereby enhancing the overall efficiency and responsiveness of the system. This requires not only a well-integrated ERP system but also one that is capable of real-time analytics to support the continual adjustments needed in a flexible production system.

To conclude, SKF employees underline the importance of implementing a more advanced system that could support the decision-making process within Flexible Flow. As for Simplified Flow, it is considered that the current system could be utilized to improve the decision-making process, not necessitating investments in a more advanced system. Slack and Lewis (2006) imply that an advanced and well-integrated system could support planners and provide real-time and informed recommendations.

5.3 MCDA

To compare and evaluate the two production scenarios and find out which one is most optimal for SKF, an MCDA was developed. This methodology integrates various decision criteria to enable a quantitative assessment, comparing both proposed production scenarios with the existing production system. Initially, the first decision criteria were established through structured interviews where SKF personnel ranked project KPIs based on perceived importance. For the second criterion, the impact of both the current and proposed production scenarios on each KPI was qualitatively evaluated and then quantified. This quantification aids in facilitating a comprehensive comparison across all scenarios. According to Gamper et al. (2006) and Linkov and Moberg (2012), involving SKF staff in the ranking process ensures that the assessment aligns with a consensus-driven approach, incorporating the needs and expectations of all stakeholders.

5.3.1 Input to MCDA

The results gathered from the eight interviewees regarding the importance of each KPI revealed both commonalities and variations. To ensure consistency, an introduction to each KPI was provided to each interviewee prior to ranking. This approach was deemed necessary to ensure a proper understanding of the KPIs by all interviewees. All respondents uniformly ranked availability as the most important KPI. Rankings for the remaining KPIs, however, varied more widely. The ranking system used assigned the top-ranked KPI a score of 4, the next a score of 3, and so forth. Additionally, respondents could assign equal importance to two KPIs, in which case the score for these was calculated as the average of their ranks. For example, if stock and ease of planning & execution were both ranked second, each would receive a score of 2.5, calculated as $(3+2)/2$. The least important KPI received a score of 1. The average weight for each KPI was then determined by dividing the total score for each KPI by the number of respondents, i.e., eight. The complete result from the rankings can be seen in Table 7.

Table 7 Results from the Rankings

Interviewee	Weight			
	Availability	Capacity Utilization	Stock	Ease of Planning & Execution
1	4	3	1,5	1,5
2	4	3	1	2
3	4	2,5	2,5	1
4	4	2	1	3
5	4	3	1	2
6	4	1	3	2
7	4	1	2	3
8	4	1	3	2
Average Weight	4	2,06	1,88	2,06

Figure 14 presents a radar chart illustrating the ranking results from the eight respondents for enhanced clarity. The chart distinctly highlights that availability is deemed highly important by all personnel, consistently receiving the maximum score of 4. It also displays the varied importance assigned to the remaining KPIs, which likely reflects the diverse roles of the interviewees within the company.

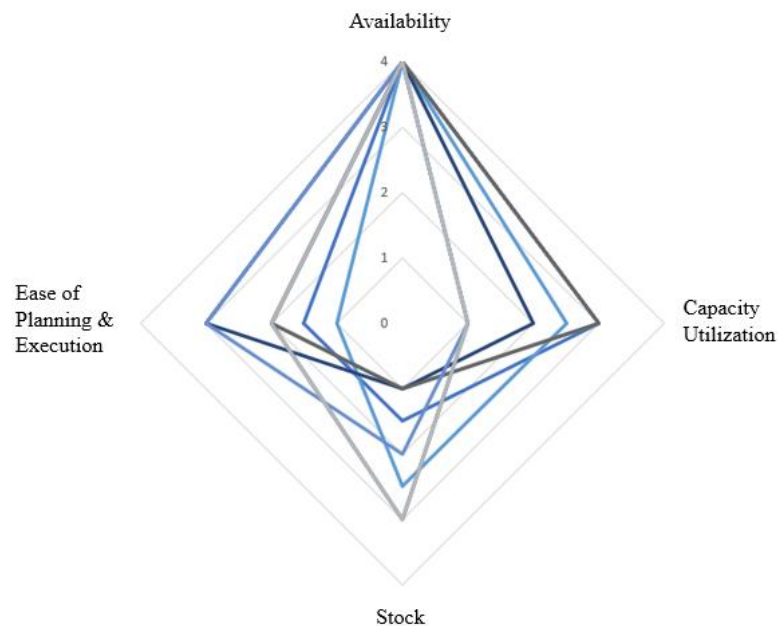


Figure 14 KPI Rankings by The Interviewees

To evaluate the impact of each scenario on the KPIs, a 3-point scale was utilized with levels categorized as low, medium, and high. Each level was assigned a corresponding quantitative value of 1 for low, 2 for medium, and 3 for high. The scale's definition for each level can be found in Table 8 below. Each scenario was compared with the KPIs, using this scale to determine which level of impact each scenario would have.

Table 8 Definition of Each KPI Level

KPI	Level	Definition
Availability	<i>Low</i>	Frequent occurrences where the necessary rollers are not available at bearing assembly on time
	<i>Medium</i>	Rollers are mostly available at bearing assembly when needed.
	<i>High</i>	Rollers are always available at bearing assembly when needed
Stock	<i>Low</i>	Significant surplus in inventory
	<i>Medium</i>	Slight surplus in stock levels but manageable
	<i>High</i>	Optimal stock levels to meet the availability with no excess or shortage
Ease of Planning & Execution	<i>Low</i>	Complex, time-consuming, and high effort required for planning and execution
	<i>Medium</i>	Some challenges but overall manageable
	<i>High</i>	Simple, efficient, and low effort required for planning and execution
Capacity Utilization	<i>Low</i>	Large portions of capacity are underused
	<i>Medium</i>	Capacity is sufficiently used but there is room for improvement
	<i>High</i>	Ability to fully utilize capacity efficiently

Before proceeding with the actual MCDA, it was necessary to score each production system: the current production system, the Simplified Flow Scenario, and the Flexible Flow Scenario, based on their anticipated impact on each KPI. The anticipated impact on each KPI was drawn from observations, interviews, and the literature review. The rationale for assigning specific scores to particular scenarios and KPIs is detailed below.

Current Production System

Availability: The current production system excels in maintaining high availability, as it consistently ensures timely delivery of rollers to the bearing assembly line during current production- and demand levels. Consequently, this system receives the maximum score of 3 for availability, indicating its effectiveness in this area.

Stock: As indicated in the VSM for the current production flows of RRY4-5 and DRQ2, there is a noticeable excess of stock within these systems. This substantial surplus, evident in both production and storage locations, has been identified as a key issue with the current production system. Consequently, according to the defined scoring criteria, this situation is assessed at a low level with a score of 1.

Ease of planning & execution: A medium score of 2 is assigned due to the complexities arising from necessary coordination between supply chain planners and production employees. Although planning and execution functions are effectively meeting current demand, the considerable flexibility within the current production system occasionally leads to synchronization challenges between the planning and execution phases. This misalignment necessitates the use of personal judgment by production personnel to make decisions, underscoring the medium-level impact on the system's overall efficiency.

Capacity utilization: The current production system, characterized by a combination of push-pull dynamics and significant stock levels, exhibits medium capacity utilization, justifying a score of 2. The VSM also reveals that uptime across various operations in the production flows RRY4-5 and DRQ2 varies between 64% and 85%. This variability indicates the potential for enhancing operational efficiency.

Simplified Flow

Availability: One drawback of the Simplified Flow Scenario is the increased risk associated with disruptions in the flow. If disruptions occur, the processing of rollers within that flow halts until the issues are resolved, thereby affecting availability. However, embracing Liker's (2004) concept of real flexibility suggests that a flow-efficient production system is better equipped to respond to demand variations. By addressing potential disruptions and viewing them as opportunities for process improvement, the system is more likely to meet the fluctuating demands of bearing assembly. Implementing not just a simplified flow but also a system that supports a pull-based, flow-efficient production, ensures that maintaining high availability levels should not pose a problem, thereby justifying a score of 3.

Stock: With the flow efficient layout, and the facilitation of only producing what is needed, the amount of inventory that sits within the system would see a decrease, in alignment with Modig and Åhlström (2012) who highlight the possibility of having lower inventory levels when focusing on flow efficiency. This reduction is further enhanced by a pull-based system, which triggers production based on actual demand rather than forecasted estimates, thereby minimizing overproduction and excess stock. The score is thereby considered to be a 3.

Ease of planning & execution: Comparing the degree of effort and efficiency needed for planning and execution between the current production system and the Simplified Flow, it would be less time-consuming, easier, and more efficient in a simplified flow due to a smaller number of parameters that need to be taking into account when doing the planning and converting it to execution. Always knowing which route each type of roller should take, with a

great potential for reducing the stock levels, the ease of planning & execution would only see a positive reaction to having a simplified flow, thereby scoring a 3.

Capacity utilization: Simplified Flow prioritizes flow efficiency over resource efficiency. While this approach aims to maximize value-adding time and minimize waste, it may result in lower resource utilization. As mentioned by Modig and Åhlström (2012), having high flow efficiency and low resource utilization results in the production system being signified as an efficient ocean. In other words, meeting customer expectations is given more importance than utilizing the full capacity of the system. Thus, the assigned score is 1.

Flexible Flow

Availability: A more flexible system that permits rollers to follow varying routes in production and to be transferred between processes facilitates rapid adaptation to disruptions, still ensuring the supply of rollers to internal customers. However, the scenario's resemblance to a functional layout and its emphasis on resource efficiency present challenges in accommodating demand fluctuations, aligning with Liker's (2004) views on real flexibility. This reduces the ability to meet availability requirements, resulting in a score of 2.

Stock: Implementing a more flexible flow that has a higher focus on resource efficiency will see an increased difficulty in applying a pull-based perspective for controlling the material flow. However, a pull-based system in this production scenario would have an increased potential if implemented successfully. As highlighted by Modig and Åhlström (2012), a focus on resource efficiency like Flexible Flow, is likely to face increased inventory levels, not contributing to lower levels than today. Despite the challenges of implementation, adopting a pull system within the Flexible Flow Scenario could effectively reduce inventory levels. This improvement in inventory management would enhance performance on this key performance indicator, meriting a score of 2.

Ease of planning & execution: Managing the Flexible Flow Scenario effectively demands an advanced ERP system, particularly when employing a fully utilized push method, which is not currently in use. Slack and Lewis (2015) highlight that while an ERP system can facilitate decision-making in production planning, its success hinges on thorough integration. Consequently, a flexible flow is likely to complicate and extend the planning process. However, implementing a pull system could simplify planning within this production scenario. Therefore, if a pull system is adopted, the score for ease of planning & execution can remain as medium, a 2.

Capacity utilization: An increased focus on resource efficiency, as seen in Flexible Flow, will positively impact capacity utilization compared to the current production system. According to Modig and Åhlström (2012), efficient islands have high resource utilization and low flow efficiency. Moreover, Bellgran and Säfsten (2010) mention that flexibility in the system can be used to handle disturbances in the production system, further increasing capacity utilization by manufacturing in other machines. This means that by prioritizing resource utilization, along with having flexibility in rerouting the rollers from Flexible Flow, the score for capacity utilization results in 3, higher than the other two scenarios.

5.3.2 MCDA Result

In Table 9 below, the final result of the MCDA is presented. Based on the explanations for each score in the previous section, Simplified Flow, the simplified flow, has the highest score in the production system, achieving a total combined score of 25,9. Both the current production system and Flexible Flow resulted in a combined score of 22,1. Each production system has high performance on availability, scoring 12 points each. Simplified Flow excels in the KPI stock and ease of planning & execution. Flexible Flow has the highest score when it comes to capacity utilization. The current production system has its lowest score on stock and performs medium on both ease of planning & execution and capacity utilization.

Table 9 Final Result of MCDA

KPI	Weights	Current State		Simplified Flow		Flexible Flow	
		Score	Weighted Score	Score	Weighted Score	Score	Weighted Score
Availability	4,0	3	12,0	3	12,0	2	8,0
Stock	1,88	1	1,9	3	5,6	2	3,8
Ease of Planning & Execution	2,06	2	4,1	3	6,2	2	4,1
Capacity Utilization	2,06	2	4,1	1	2,1	3	6,2
Combined score			22,1		25,9		22,1

For visualization purposes, the results for the different production systems on each KPI are shown in Figure 15 below. Highlighting in what KPI each system excels and where they do not.

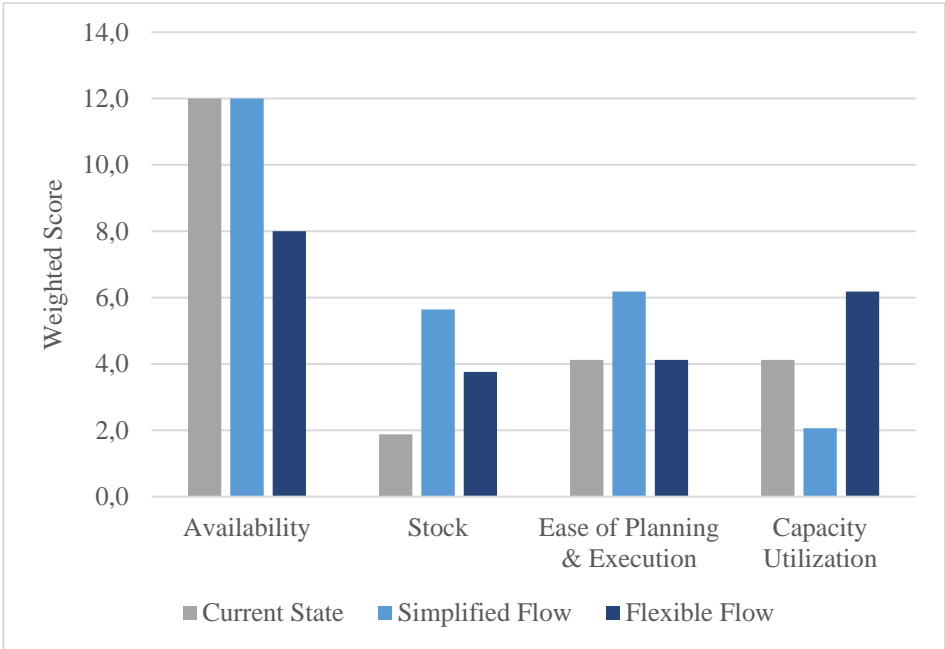


Figure 15 Graphs Showing Weighted Score on Each KPI

The combined score for the total score of the three production systems based on the results of each of the KPIs, is shown in Figure 16 below. Highlighting that the simplified flow is best in

the current situation at SKF. Highlighting that the simplified flow is best in the current situation at SKF.

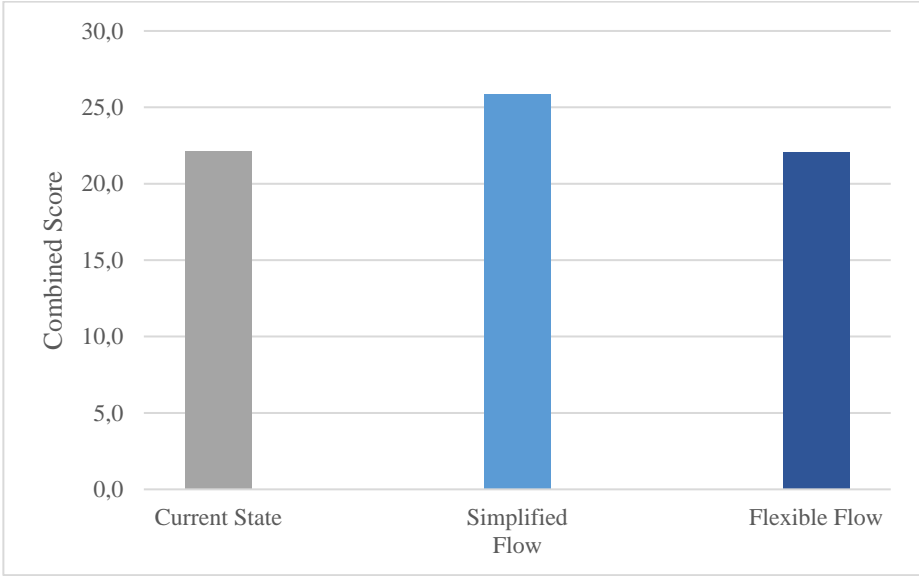


Figure 16 Combined Score of Current State, Simplified Flow, and Flexible Flow

5.4 Summary of Results

In order to draw a final conclusion and determine which production scenario would be the most suitable for the roller production of SKF, a thorough analysis of the results obtained from both the MCDA and the assessment of how each production scenario addresses the identified problem areas has been taken into account.

The MCDA analysis reveals that Simplified Flow, with its focus on flow efficiency and streamlined production paths for the rollers, outperforms Flexible Flow when evaluated against the KPIs of the project and compared to the current production flow. When examining the identified problem areas and how each production scenario addresses them, Simplified Flow enables an easier implementation of pull, which allows production on a need basis. However, implementing pull in the Flexible Flow could have a heavier impact than for the Simplified Flow, enabling improvements in both stock and ease of planning & execution.

The Simplified Flow Scenario, with its focus on flow efficiency, better facilitates a decrease in lead times and enables a reduction in batch sizes. Furthermore, given the description of real flexibility by Liker (2004), the Simplified Flow could outperform the Flexible Flow in flexibility. This means that, according to the theory of real flexibility, Simplified Flow could handle variations in demand more efficiently, meaning that the Flexible Flow might not be so flexible.

The Flexible Flow outperforms in handling disruptions in the production system, given its ability to utilize different resources whenever there are breakdowns. As for the production in Simplified Flow, it would be idle until the resource is fixed, which could increase the downtime of roller production heavily. However, a positive outcome of this is that disruptions in production are handled directly and are visible.

Considering these factors and the current situation, a degree of flexibility in the production system is necessary. Consequently, the response to RQ4 suggests that SKF should adopt

Simplified Flow for its emphasis on simplicity, but also incorporate the minimal flexibility needed, such as an alternative route for the rollers, to accommodate potential disruptions to a certain extent. Once the pull-based system is implemented and functioning effectively, the focus could shift towards increasing total output if demand is increasing, which may require further enhancements to flexibility.

6. Discussion

In this chapter, a discussion is carried out with a focus on providing the reader with additional insight from the author's perspective to the result previously presented. A discussion about parts of the methodology and the KPIs of the project, along with some challenges further ahead, is discussed as well.

The purpose of the thesis is to identify the most suitable production system for SKF's roller production. This involves gaining an understanding of the existing production system and carrying out an evaluation of the two potential production scenarios that were conceptualized by SKF. The objective is to assist the company in determining which production system aligns best with its production environment, with the goal of creating a long-lasting solution.

In this study, a set of four KPIs was utilized to assess the current production system and the production scenarios. These KPIs include availability, stock, ease of planning & execution, and capacity utilization. SKF employees introduced these KPIs at the outset of the project and they were subsequently employed throughout the duration of the study.

However, it would have been advantageous to discuss the KPIs and their objectives beforehand. Moreover, analyzing the potential interconnectivity between certain KPIs could have provided a different perspective on the outcome of the study. It is possible that some KPIs may have a positive or negative impact on others, and therefore correlates with each other. Additionally, it is worth noting that some KPIs in this study are quantifiable while others fall more under a principle or value-based category and cannot be quantified. Capacity utilization, stock, and availability can all be quantified, whereas ease of planning & execution falls more under a value-based category. In hindsight, the KPIs could have been named differently, perhaps as organizational requirements, as they were deemed crucial by SKF.

The first research question aims to gain a better understanding of the current roller production at SKF. The primary method used for this is VSM. In mapping the current state, the two flows of RRY4-5 and DRQ2 are visualized, encompassing all roller dimensions. This approach is chosen because all rollers can be considered part of the same product family. However, including all rollers in the VSM might make it overly holistic. For instance, some mean values need to be calculated when collecting data for the VSMs. Nevertheless, the VSMs provide substantial insights, and the holistic view can also be advantageous. However, if needing a more detailed VSM, it is of high interest to consider performing a VSM on more specific roller dimensions to gain further insights and to see the differences in the results.

By analyzing the current state map and conducting interviews with SKF personnel, RQ2, which is to identify problem areas in the current situation, is answered. The current state map shows the need to calculate the takt time for the production system, which is currently not done in roller production. However, the results have shown that calculating the takt time for the Simplified Flow might not be as crucial as for the Flexible Flow. For clarification purposes, takt time always exists in a production system, calculated from customer demand and available working hours. However, the necessity of calculating and controlling the flow using the takt time can vary, and, in this case, the Flexible Flow has a higher necessity for controlling the flow using the calculated takt time than in the Simplified Flow.

The results for RQ2 also reveal a high level of excess inventory in the system, leading to the identification of overproduction and excess inventory as another problem area. The current state map also helps identify transport issues, particularly between R- and D-factories. Regarding the transport issue, it is currently not possible to avoid transportation between the factories, given that the necessary resources are located in both factories to produce the rollers and assemble the finished SRBs. First and foremost, the aspect of transport adds waste to the production system, making it more inefficient. Furthermore, to minimize pollution and environmental impact throughout the SKF's production system, it is necessary to consider minimizing the transport distance, by, for example, manufacturing rollers in one factory. This would not only contribute to a positive effect on the environment but also bring more simplicity into the planning of roller production, along with economic benefits.

The insights gained from RQ2 prove crucial in addressing RQ3, specifically in distinguishing and characterizing the differences between the two production scenarios. Additionally, a thorough examination of existing literature helps to clarify the theoretical disparities between the two scenarios. The first scenario, Simplified Flow, is primarily focused on optimizing flow efficiency, while the second scenario, Flexible Flow, places greater emphasis on resource efficiency. Furthermore, the scenarios differ in their layout, with Simplified Flow being more conducive to a line-based layout, and Flexible Flow resembles a functional layout. By examining the scenarios from a theoretical standpoint, it is possible to present a conceptual overview of the differences, rather than delving into specifics. By leveraging all the data collected, it is possible to gain a more practical understanding of how the scenarios would address the problem areas identified in RQ2, and as the problems derive from the SKF production system, it enables a theoretical application of the scenarios to the SKF production system.

Once RQ3 is answered, it is possible to move on to answer the main question of the thesis, RQ4: *What are the main differences between the two proposed production scenarios and how do they manage the identified problem areas?* With both quantitative and qualitative data derived from answering RQ 1-3, the MCDA, based on all available information, can be conducted. This will ultimately lead to a recommendation for SKF.

The results from the MCDA show that the Simplified Flow is the highest-performing Scenario. The main reason for this is its performance in managing the KPIs of availability, stock, and ease of planning & execution since it is outperforming the other scenarios in those KPIs. The simplicity contributes to easier management and less complexity to the system but also ensures a more predictable and controlled production environment. The results further show that simplicity helps in making the planning process of roller production less dependent on individual decision-making, it also supports using the ERP system to make recommendations on planning.

However, the study also identified some vulnerabilities to Simplified Flow, which needs to be considered as well. First and foremost, when disruptions occur, Simplified Flow's streamlined nature makes it vulnerable. Disruptions could occur for multiple reasons, e.g., breakdowns of machinery. This could lead to significant production delays since there is no way to move around the disruptions in Simplified Flow. Having the flexibility to handle these disruptions is considered necessary. Even though disruptions in the flow are generally viewed negatively when they occur in Simplified Flow, they are forced to be managed, thereby contributing to continuous improvements and optimizing production.

Additionally, upon comparing Simplified Flow to Flexible Flow from the results of the MCDA, it becomes evident that the capacity utilization of Simplified Flow is lower. This suggests that achieving high levels of capacity utilization in the production system may pose challenges for Simplified Flow, particularly if customer demand is centered on a single type of roller that is solely produced in one particular production flow. Consequently, other production flows that are designated for different types of rollers may remain inactive, as there is no demand for those specific types. Worth noting, is that even though capacity is being fully used, this does not mean that it is being used in the most efficient way. If there is no need to produce and machines still operate and manufacture rollers, this will only contribute to overproduction and excess inventory.

Building upon the previous discussion about the KPIs and their objectives, and that there could be some interconnectivity that would have been advantageous to analyze, another effect that this would give to the study is the possibility of a more in-depth MCDA. If being able to find how the KPIs relate to each other, or even if they should have been changed to some other KPIs, more detailed criteria could have been established, providing further enhancement to the results from the MCDA.

Based on the interviews conducted, it has been revealed that there could be a potential challenge with regard to meeting the future demand, which is expected to rise. This could pose a significant issue as the existing roller production capacity may not be adequate to meet the needs of the internal customers if they were to assemble the SRB at its maximum pace. Therefore, it is crucial to consider and devise ways to improve the roller production capacity to ensure that the production requirements are met adequately in the future. One possible way to do this is to further reduce the setup times of the resources, which enables SKF to make improvements in resource uptime, reducing batch sizes and moving further toward continuous flow in the production system. To further enhance this, implementing aspects from the Flexible Flow, which has a higher potential to reach an increased total output for rollers, thereby the reason for not only adapting a fully simplified flow but instead using some form of alternative routes for the rollers in the system.

Furthermore, in the future, SKF could consider gradually moving towards more flexibility in terms of coping with unexpected circumstances and disruptions of the resources in production. As described in the sand cone model in section 3.7.1, Figure 9, adapted from Slack and Lewis (2015) and Bellgran and Säfsten (2010), to achieve flexibility in a production system it is essential to perform well in the performance objectives of quality, dependability, speed, and cost, first. Hence, SKF can focus on the other performance objectives first, and the production system would then naturally be more flexible given the high performance in quality for their rollers, dependable machinery, speed in the system and an efficient production system focused on reducing waste and cost. It should be noted that flexibility, in terms of adding more machines to handle disruptions, is not the same as the performance objective flexibility described by Slack and Lewis (2015) and Bellgran and Säfsten (2010). The flexibility described by the authors is gained when having an efficient production system, fulfilling the previous performance objectives, where it is possible to handle changes in demand but also handle disruptions in production.

The overall efficiency of a production system heavily impacts the effects on the triple bottom line aspects; economic, social, and environmental. For the environmental aspect, the production system should be formed to minimize waste, that way, the production system will utilize less energy. As mentioned, by reducing transport distance, it is possible to minimize pollution and environmental impact. Thus, moving toward a more simplified flow, it is possible to achieve a more sustainable production given the focus on flow efficiency. Moreover, the economic aspect benefits from achieving a more efficient production system as well. A more efficient system can lower the costs of transportation and minimize tied-up capital for storage. The social aspect regards the well-being of the employees, in an efficient production system, with structured and streamlined processes, it is possible to continuously evaluate and improve the working conditions for the personnel.

7. Conclusion

The purpose of this thesis is to identify the most suitable production system for SKF roller production by evaluating two production scenarios, Simplified Flow and Flexible Flow, conceptualized by the company. The main research question, “*Which of the two proposed production scenarios for SRB rollers is most suitable for SKF?*”, is therefore answered by primarily getting an understanding of the current situation that SKF and the roller production are operating in, followed by how respective production scenario manages each identified problem areas derived from the current state analysis. Finally, a conclusion is made from the addition of how each production scenario is performing against the four KPIs of availability, stock, ease of planning & execution, and capacity utilization, with the use of the MCDA.

In Chapter 4, the current situation at SKF is described, where the VSM for the two production flows of RRY4-5 and DRQ2 is presented with the six identified problem areas included. Chapter 5 contains descriptions of the production scenarios, with the Simplified Flow resembling more of a line layout with a higher focus towards flow efficiency, whereas the Flexible Flow utilizes a functional layout with a higher focus towards resource efficiency. This chapter also presents how the production scenarios will address the problem areas outlined in Chapter 4. The results show that by implementing the conceptualized production scenario of Simplified Flow, SKF will see a positive reaction to most of the problem areas with the reason being its ability to reduce lead times, complexity in planning, reduction of batch sizes, and flexibly meet variations in demand.

Additionally, the MCDA based on interviews and theory is presented to quantitatively calculate which scenario performs best on the KPIs considered important by SKF. The result from the MCDA shows yet again that Simplified Flow outperforms both the Flexible Flow and the current production system.

The main drawback to the Simplified Flow compared to the Flexible Flow is its ability to manage disruptions in the flow in the sense that the production would have to stop and wait until the disruption is handled. Also, the Simplified Flow could see potential difficulties in meeting increasing demand in the future. Because of this, it appears that some degree of flexibility to the production flow is needed.

The answer to the main research question, “*Which of the two proposed production scenarios for SRB rollers is most suitable for SKF?*”, is, therefore, to move towards the Simplified Scenario, further described below where recommendations to the company are presented.

7.1 Recommendations

A shift from the current production system of rollers towards the Simplified Flow scenario is recommended for SKF. This should not be mistaken for a direct transition to the scenario, but instead to move towards the simplicity that the scenario is given with its advantages mentioned in this study.

The reason for not implementing the Simplified Flow directly is that the production system needs some degree of flexibility, which the current situation and the Flexible Flow can offer. Therefore, by moving towards the Simplified Flow, where the roller dimensions do have specific routes in the production system, alternative routes for the rollers are needed, thereby utilizing a hybrid solution to accommodate benefits from both production scenarios. These

alternative routes will work as a safety function, protecting the flow in the system when disruptions occur or when there is a higher demand on certain roller dimensions.

Further, another recommendation to the company is to question the hybrid format of push and pull currently used to control the production system, and to fully implement pull-based principles instead. More specifically, this means that instead of having production orders for rollers be based on calculations from the ERP system taking forecasts into account, they should only be based on what is needed from the bearing assembly channels, by utilizing some form of re-order system, like a re-order point, thereby only producing what is needed, neither more nor less.

7.2 Further Research

Moving toward Simplified Flow through the establishment of alternative routes necessitates more in-depth research. This research should focus on determining which roller dimensions will be assigned to specific flows and which routes will serve as alternatives for each dimension. Additionally, practical aspects such as production capacity, demand volumes, and other relevant factors for both roller production and bearing assembly must be considered. It is crucial to ensure a balanced match between these factors, preventing any one element from outpacing the others. The assigned routes for each roller dimension must also align with both current and anticipated production demands to maintain efficiency.

Conducting a future state map for each scenario is also to be suggested as further research, enabling visualization of the predicted outcome. Establishing this future state map can be done by answering the 8 steps presented by Rother and Shook (2004). This future state map in combination with the more in-depth practical aspects, would facilitate a possible simulation of the outcome of the two production scenarios, further contributing to the decision-making process. Whether or not it is a simulation, the emphasis should be on putting the chosen strategy to the test before implementing it over the whole production system. It could be with a detailed simulation or a practical implementation in one part of the production system. When seeing that it works properly, a full implementation can be made.

Furthermore, a continued analysis of the KPIs utilized in the study should be conducted, to see whether any of them are interconnected in some way. This could help in understanding the effects of the scenarios further.

References

- Astute Analytica. (2023, March 10). *Global Bearing Market to Hit Sales of US\$ 163.7 Billion by 2031 | SKF and Schaeffler LTD Collectively Capture More than 36% Revenue Share: Astute Analytica*. Retrieved from GlobeNewswire: <https://www.globenewswire.com/news-release/2023/03/10/2624928/0/en/Global-Bearing-Market-to-Hit-Sales-of-US-163-7-Billion-by-2031-SKF-and-Schaeffler-LTD-Collectively-Capture-More-than-36-Revenue-Share-Astute-Analytica.html>
- Axsäter, S. (1991). *Lagerstyrning*. Lund: Studentlitteratur.
- Bączkiewicz, A., Wątróbski, J., Kizielewicz, B., & Sałabun, W. (2021). Towards Objectification of Multi-Criteria Assessments: a Comparative Study on MCDA Methods. *Proceedings of the 16th Conference on Computer Science and Intelligence Systems*, pp. 417–425, isbn: 9788395918384. doi: 10.15439/2021F61.
- Bandyopadhyay, S. (2020). Comparison among some multi-criteria decision analysis techniques. *Proceedings of the 2020 International Conference on Computing, Communication and Security*. doi:10.1109/ICCCS49678.2020.9277166
- Bell, E., Bryman, A., Harley, B., & Bryman, A. (2019). *Business research methods* (5th ed.). Oxford University Press.
- Bellgran, M., & Säfsten, K. (2010). *Production Development over Time*. In: *Production Development*. Springer, London. doi:https://doi.org/10.1007/978-1-84882-495-9_1
- Belton, V., & Stewart, T. J. (2002). *Multiple criteria decision analysis an integrated approach*. Boston: Kluwer Academic Publishers.
- Bennett, D. (1986). *Production Systems Design*. Butterworths.
- Blaxter, L., Hughes, C., & Tight, M. (2006). *How to Research* (3rd ed.). Open University Press, Berkshire UK.
- Bosch, K., Bryman, A., & Liao, T. (2014). *The SAGE Encyclopedia of Social Science Research Methods*. London: SAGE Publications.
- Bryman, A. (2012). *Social research methods*. Oxford University Press.
- Bryman, A., & Bell, E. (2011). *Business Research Methods* (3rd ed.). Oxford University Press.
- Chahal, V., & Narwal, M. S. (2017). Impact of Lean Strategies on Different Industrial Lean Wastes. *International Journal of Theoretical and Applied Mechanics*, 275-286.
- Chen, C. K., Palma, F., & Reyes, L. (2019). Reducing global supply chains' waste of overproduction by using lean principles: A conceptual approach. *International Journal of Quality and Service Sciences*, 441-454.
- Chiarini, A. (2012). *Lean organization: from the tools of the Toyota Production System to lean office* (3rd ed.). Springer Science & Business Media.
- Choudari, S. C., Adil, G. K., & Ananthakuma, U. (2010). Congruence of manufacturing decision areas in a production system: a research framework. *International Journal of*

- Damelio, R. (2011). *The Basics of Process Mapping, 2nd Edition*. CRC Press.
- Dangayach, G., & Deshmukh, S. (2001). Manufacturing strategy. *International Journal of Operations & Production Management*, 21(7), 884–932. doi:10.1108/01443570110393414
- Deif, A. M., & ElMaraghy, H. A. (2017). Variety and volume dynamic management for value creation in changeable manufacturing systems. *International Journal of Production Research*, 55(5), 1516-1529. doi:10.1080/00207543.2016.1222088
- Dennis, P. (2007). *Lean production simplified : a plain language guide to the world's most powerful production system* (Vol. 2). New York: Productivity Press.
- Doran, G. T. (1981). There's a S.M.A.R.T. way to write managements's goals and objectives. *Management Review*, 70(11), 35-36.
- Eaton, M. (2013). *The lean practitioner's handbook* (1st ed.). Kogan Page, London;Philadelphia.
- Gamper, C., Thöni, M., & Weck-Hannemann, H. (2006). A conceptual approach to the use of Cost Benefit and Multi Criteria Analysis in natural hazard management. *Natural Hazards and Earth System Sciences*, 293–302.
- Goldratt, E. M., & Cox, J. (1992). *The goal: a process of ongoing improvement*. North River Press. Inc.: Great Barrington, MA.
- Groten, M. G.-G. (2021). A Systematic Improvement Model to Optimize Production Systems within Industry 4.0 Environments: A Simulation Case Study. *Applied Sciences*, 11(23), 11112. doi:10.3390/app112311112
- Groten, M., & Gallego-Garcia, S. (2021). A Systematic Improvement Model to Optimize Production Systems within Industry 4.0 Environments: A Simulation Case Study. *MDPI*, 11(23), 11112. doi:10.3390/app112311112
- Hancock, D. R., & Algozzine, B. (2015). *Doing Case Study Research: A Practical Guide for Beginning Researchers* (2nd ed.). Teacher College Press.
- Heher, Y. K., & Chen, Y. (2017). Process mapping: A cornerstone of quality improvement. *Cancer Cytopathology*, 125(12), 887-890. doi:org/10.1002/cncy.21946
- Helleno, A., Pimentel, C., Ferro, R., Fernando Santos, P., Oliveira, M. C., & Tadeu Simon, A. (2015). Integrating value stream mapping and discrete events simulation as decision making tools in opeation management. *The international Journal of Advanced Manufacturing Technology*, pp. 77(9-12), 1759–1767. <https://dx.doi.org/10.1007/s00170-015-7087-1>.
- Hill, A. (2009). *Manufacturing Operations Strategy*. Palgrave Macmillan.

- Hopp, W. J., & Spearman, M. L. (2004). To Pull or Not to Pull: What Is the Question? *Manufacturing & Service Operations Management*, 133-148, <https://doi.org/10.1287/msom.1030.0028>.
- Ishizaka, A., & Newmery, P. (2013). *Multi-Criteria Decision Analysis : Methods and Software*. Newark : John Wiley & Sons.
- Johannson, E., & Johannson, M. (2006). Materials supply systems design in product development projects. *International Journal of Operations & Production Management*, 26(), 371 - 393. doi:10.1108/01443570610650549
- Jonsson, P., & Mattson, S.-A. (2009). *Manufacturing Planning and Control*. McGraw Hill Higher Education.
- Jonsson, P., & Mattsson, S.-A. (2016). *Logistik: läran om effektiva materialflöden* (Vol. 3rd edition). Lund: Studentlitteratur AB.
- Khojasteh, Y. (2016). *Production Control Systems*. Springer Tokyo.
- Koren, Y., & Shpitalni, M. (2010). Design of reconfigurable manufacturing systems. *Journal of Manufacturing Systems*, 29(4), 130–141. <https://doi.org/10.1016/j.jmsy.2011.01.001>
- Lee, H. L., Padmanabhan, V., & Whang, S. (1997). The bullwhip effect in supply chains. *Sloan management review*, 93-102.
- Li, L., Chang, Q., Ni, J., & Biller, S. (2009). Real time production improvement through bottleneck control. *International Journal of Production Research*, 47(21), 6145-6158. doi:10.1080/00207540802244240
- Liker, J. K. (2004). *The Toyota way : 14 management principles from the world's greatest manufacturer*. New York : McGraw-Hill.
- Liker, J. K., & Meier, D. (2006). *The Toyota Way Fieldbook*. McGraw-Hill Education.
- Linkov, I., & Moberg, E. (2012). Multi-criteria decision analysis - environmental applications and case studies. *CRC Press Taylor & Francis Group*.
- Locher, D. (2008). *Value Stream Mapping for Lean Development*. New York: Productivity Press.
- Lumsden, K. (2007). *Fundamentals of logistics*. Chalmers University of Technology.
- Manu, G., Kumar M, V., Nagesh, H., Jagadeesh, D., & Gowtham, M. (2018). Flexible Manufacturing Systems (FMS), A Review. *International Journal of Mechanical and Production Engineering Research and Development*, 8, 323-336. doi:10.24247/ijmperdapr201836
- Modig, N., & Åhlström, P. (2012). *This is lean: Resolving the efficiency paradox*. Rheologica.
- Noreen, E. W., Smith, D. A., & Mackey, J. T. (1995). *The Theory of Constraints and Its Implications for Management Accounting*. North River Press.

- Olhager, J., & Östlund, B. (1990). An integrated push-pull manufacturing strategy. *European Journal of Operational Research*, 45(2-3), 135-142. doi:10.1016/0377-2217(90)90180-J
- Olhager, J., & Rudberg, M. (2002). Linking manufacturing strategy decisions on process choice with manufacturing planning and control systems. *International Journal of Production Research*, 40:10, 2335-2351, DOI: 10.1080/00207540210131842.
- Pozo, H., Roque da Silva, O., Tachizawa, T., & Liu, S. (2017). The influence of performance objectives on the implementation of lean manufacturing practices: An analysis based on strategic groups. *Cogent Business & Management*, 4(1). doi:10.1080/23311975.2017.1405718
- Preston, A. (2022, July 8). *Skill Dynamics*. Retrieved from <https://skilldynamics.com/blog/understanding-the-bullwhip-effect-in-supply-chains/>
- Ptak, C., & Smith, C. (2011). *Orlicky's Material Requirements Planning, 3rd ed.* McGraw-Hill Professional.
- Rahani, A. R., & Al-Ashraf, M. (2012). Production flow analysis through value stream mapping: A lean manufacturing process case study. *Procedia Engineering*, 41, 1727-1734. doi:10.1016/j.proeng.2012.07.375
- Rother, M., & Shook, J. (2003). *Learning to See: Value-stream mapping to create value and eliminate muda*. Brookline, Lean Enterprise Institute.
- Ryen, A. (2004). *Kvalitativ intervju: från vetenskapsteori till fältstudier*. Malmö: Liber ekonomi.
- Singh, S. (2018, January 11). What is the bullwhip effect and How do you minimize it?
- SKF. (2022). *Annual report*. Retrieved from <https://investors.skf.com/sites/skf-ir/files/pr/202303013297-1.pdf>
- SKF. (2023). *Annual report*. Retrieved from <https://investors.skf.com/sites/skf-ir/files/pr/202403039498-1.pdf>
- SKF Internal Document. (2024, 02 19). Channel Concept Booklet.
- Slack, N., & Brandon-Jones, A. (2019). *Operations management* (Vol. 9th edition). Pearson.
- Slack, N., & Lewis, M. (2015). *Operations Strategy* (Vol. 4th ed). Pearson Education Limited.
- Slack, N., Brandon-Jones, A., & Johnston, R. (2013). *Operations Management 7th Edition*. Harlow: Pearson Education Limited.
- Slack, N., Chambers, C., & Johnston, R. (1995). *Operations Management*. London: Warwick Business School.
- Sörqvist, L., & Bergendahl, M. (2021). *Lean: Processutveckling med fokus på kundvärde och effektiva flöden* (Vol. 2). Lund: Studentlitteratur AB.

Stevenson, J. W. (2005). *Operations Management, 8th ed.* McGraw-Hill Irwin.

Tamás, P., & Hermans, M. (2023). Improving the efficiency of maintenance process in manufacturing systems using industry 4.0 tools.

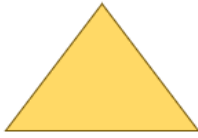
Tomkins, J. (1996). *Facilities planning* (Vol. 5th edition). New York: Wiley.

Zandin, K. B. (2001). *Maynard's Industrial Engineering Handbook, Fifth Edition.*

Appendix A

Data Scheet when Gathering Data for the Current State Map

Buffer/Storage



Amount

Process
Number of Operators
C/T Cycle Time
Process Time
Setup Time
Uptime
Batch Size
Shift, working time







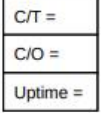

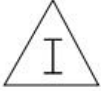
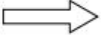



Comments

Transport
Frequency
Distance

Batch Order
Where from
Frequency

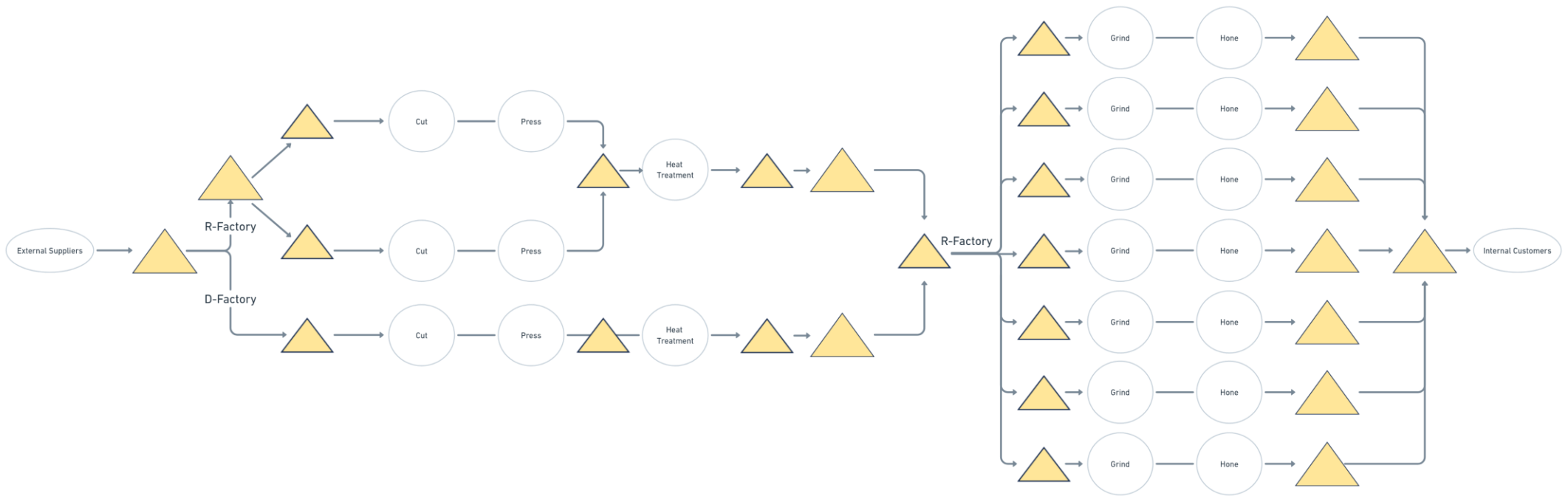
Appendix B

Symbols used in Value Stream Mapping

	Supplier or Customer	Used to identify suppliers and customers		Timeline	Used to record value and non-value added time
	Internal Process	Used to identify major process steps		Go see production	Used to indicate data gathered by measuring and seeing production in-person
	Shared Process	Used to identify shared process steps		Operator	Used to indicate number of operators in a process
	Data Box	Used to record relevant data		Electronic Information	Used to indicate electronic information
	Inventory	Used to record inventory at each process step			
Qty					
	Material Movement (Finished/Raw goods)	Raw or finished goods moved from supplier or to customers			
	Shipment Arrow	Material moved between storage and processes with forklifts			
	Truck Movement	Used to identify shipping using trucks, from external supplier and finished goods deliveries			
Frequency / Distance					
	Forklift Movement	Used to identify material movement with forklifts			

Appendix C

Flow Chart of SKF Roller Manufacturing



DEPARTMENT OF TECHNOLOGY MANAGEMENT AND ECONOMICS
Division of Supply and Operations Management
CHALMERS UNIVERSITY OF TECHNOLOGY

Gothenburg, Sweden
www.chalmers.se



CHALMERS
UNIVERSITY OF TECHNOLOGY