Production process design in the sheltered workshop of VMI

Master thesis - Production and Logistics Management

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Management summary

VMI is a leading machine manufacturer for the tire, rubber, can, and care industry. Its manufacturing location in Epe houses a sheltered workshop for the mechanical assembly of high-volume, low-variety products: production group E720. Their products relate to modules with intellectual property (IP), of which VMI allows manufacturing only to be in Epe. In recent years, the production processes of the sheltered workshop have not evolved with the increasing production quantities. The facility layout, material supply, and working conditions are relevant aspects of the production process design that do not match the current product characteristics. The results are a loss in productivity and too low process capacities. In addition, VMI plans to expand the product portfolio of the sheltered workshop in the future, which will further increase the workload. Therefore, VMI desires to realise high-capacity production processes in the short term to prepare the sheltered workshop for the future. The research focused on one pilot production process to demonstrate and exercise various methodologies. As for the other production processes, the applicability of the approach depends on a viable new process design. Hence, the main research question is as follows:

How can a specific pilot production process of production group E720 be redesigned such that the annual production capacity increases considerably while the number of employees remains intact?

To answer this question, we employed the DMAIC methodology dividing the research into the five phases define, measure, analyse, improve, and control. Research in these phases was supported by interviews, personal observation, literature research and a realistic pilot. In particular, the literature used was diverse, ranging from process planning to the scheduling of production orders. Results of each of the five phases follow below.

The product selection in the *define* phase selected the lever for a new production process design. Firstly, the lever has growth and potential. Secondly, it has by far the largest share in production hours and quantities of any product in the product portfolio. Thirdly, it is an IP-related product, which means the assembly of levers will remain in Epe for years. Finally, the productivity of the lever assembly process decreased in recent years since the production hours were not in proportion to the annual growth in production quantities. The lever is a product family of 18 varieties varying in function (i.e., standard lever and mechanical and vacuum clip bar levers) and working length/inch size. The lever assembly is a batch process and has its dedicated production cell in the facility. Shelf racks close to the lever production cell store the components needed for the lever varieties. The master production schedule controls the material supply and schedules production orders per week.

In the *measure* phase, we determined the current performance of the lever production process in terms of quality, lead time, costs, and ergonomics. The process has an % first time right (FTR) percentage and the assembly time consists of % value-adding (VA), % necessary non-value adding (NNVA), and % unnecessary non-value adding (UNVA) activities. The absolute errors of the latter three percentages are small. In addition, the assembly costs for a standard lever (S), mechanical (M), and vacuum clip bar lever (V) are € , € , and € , respectively. Finally, the ergonomics of the lever assembly are good. Two ergonomic checklists separately indicated that the workload should not cause any health complaints. Table 1 lists the results of the process measurement and the requirements of VMI per key performance indicator.

Table 1: Overview of the current state performance of the lever assembly process.

	Quality	Lead time			Costs			Ergonomics
KPI	FTR-%	VA-%	NNVA-%	UNVA-%	Assembly costs			Ergonomic score
					S	M	V	
Req.	%	≥ %	≤ %	≤ %	€	€	€	
Current state	%	%	%	%	€	€	€	Good

The *analyse* phase focused on analysing the production process and identifying factors that cause the lever production process not to meet its requirements. It determined ten main factors that drive the current performance. We selected seven after excluding the out-of-scope drivers and a non-influenceable process characteristic. These seven drivers relate to the facility layout, material supply, process and workstation design, and work method. When we develop solutions for these main influence factors, we can potentially solve up to 77% of the current issues.

During the *improve* phase, we designed a new production process for the lever. The most fundamental changes are that the process becomes a mass process with a product layout. Furthermore, the lever assembly becomes a one-piece flow process arranged in a U-shaped layout. The new design also includes new assembly methods that should significantly improve the working conditions, ease of assembly, process quality, and health and safety of the employees. Lastly, it includes improvements in ergonomics, inventory control, material supply, quality improvement cycle, scheduling, and workstation design.

A proof of concept determined whether the new process design of the lever is feasible and verified if the new assembly methods work as envisioned. We experimented with a physical test setup that represented the new process design. The proof of concept used a sample size of 100 standard levers, determined using a 95% confidence level. It used the same key performance indicators as the baseline performance. Table 2 presents the future performance of the lever assembly process. It indicates that the FTR percentage increased from % to %. Also, the future state lever assembly consists of % VA time, an increase of %. Simultaneously, the NNVA decreased by % to %, and the UNVA declined by % to %. Table 2 also lists a decrease in the effective cycle time (CT) from minutes to minutes per standard lever. Hence, the assembly costs reduce from € to € per lever, a saving of € per lever. Moreover, the workload of the lever assembly should not cause any health complaints since the ergonomic checklists indicated good working conditions. Last and most important, the capacity of the new process increases by % with only one employee assembling levers, which is 1.7 times larger than the current demand for levers.

Table 2: Overview of the current and future state performance of the lever assembly process.

	Quality	Lead time			Costs		Ergonomics
KPI	FTR-%	VA-%	NNVA-%	UNVA-%	CT [min]	Assembly costs	Ergonomic score
Req.	%	≥ %	≤ %	≤ %		€	
Current state	%	%	%	%		€	Good
Future state	%	%	%	%		€	Good
Delta	+ %	+ %	- %	- %	-	-€	

The proof of concept demonstrated that the new production process design of the lever is feasible, and the new assembly methods worked as intended. Therefore, we created in the *control* phase an implementation plan. The implementation plan outlines all the activities VMI should carry out to realise and further improve the new process design of the lever. Figure 1 visualises the implementation plan using a roadmap. In addition, we estimated the annual benefits and the non-recurring costs for three scenarios. These scenarios vary in the further improvement of the process and product design. We selected the second scenario since it is the most realistic scenario. The second scenario expects about € of non-recurring costs and a little over € of annual benefits. It results in an ROI of months and proves that the new process design of the lever is both technically and financially feasible.

Implementation phase	Department	Activity	2022				2023
			Q1	Q2	Q3	Q4	Q1
Pre-implementation activities	Engineering	Define quality standards					
		Review two engineering fits					
		Engineering fit bush bearings/pivot block					
	Production engineering	Industrialisation process design					
		Implementation TOS concept					
	Sheltered workshop	Skill matrix					
	Warehouse	Information and material streams					
Implementation	Production engineering	Process design standard levers					
		Process design clip bar levers					
Post-implementation activities	Engineering	Redesign slide blocks					
	Production engineering	Create capable processes					
		Active monitoring ergonomics					

Figure 1: Implementation roadmap for the production process design of the lever.

The new production process design of the lever demonstrated that the applied methodologies resulted in a technically and financially feasible design. Therefore, the other production processes of the sheltered workshop can use a similar approach to realise a considerable capacity increase.

The research resulted in 13 recommendations. We mention the three recommendations that we consider most important.

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These standards should be simple and preferably of a visual nature to co-operate with the sheltered workshop. Finally, in the (near) future, VMI desires to expand the product portfolio of the sheltered workshop. However, the current portfolio already requires a relatively wide range of skills. Skills that not all employees possess or that require some practice to obtain. Therefore, we recommend that the consideration of adding a product to the product portfolio of the sheltered workshop is early on in its design phase to take the skill set of the sheltered workshop into account in the product design. The design of a product should reflect the skills of the sheltered workshop employees.

Acknowledgements

Hereby, I present my Master thesis 'Production process design in the sheltered workshop of VMI'. It finalises my study in Industrial Engineering and Management at the University of Twente. I would like to thank several people who contributed to my thesis.

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Finally, I would like to thank my family and friends for their support. My graduation period had some difficult periods where your supporting words and advice were of great value.

I hope you enjoy reading my thesis.

Willem Limpers,
March 2022

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List of abbreviations

Abbreviation	Definition	Introduced on page
CIMM	Continuous Improvement Maturity Model	121
CTQ	Critical to Quality	19
DFA	Design for Assembly	65
DMAIC	Define, Measure, Analyse, Improve, and Control	10
ERP	Enterprise Resource Planning	8
FTR	First Time Right	44
IP	Intellectual Property	2
JIT	Just in Time	55
KPI	Key Performance Indicator	27
LTIFR	Lost Time Injury Frequency Rate	21
MSA	Measurement System Analysis	31
MPS	Master Production Schedule	23
NCP	Non-Conforming Product	6
NPI	New Product Introduction	6
NNVA	Necessary Non-Value-Adding	28
PO	Production Order	20
POLCA	Paired-Cell Overlapping Loops of Cards with Authorisation	63
QESH	Quality, Environment, Safety, and Health	29
QLTCS	Quality, Lead time, Technology, Costs, and Safety	19
QRM	Quick Response Manufacturing	63
RI&E	Risk inventory and evaluation	20
ROI	Return on Investment	123
SIPOC	Suppliers, Inputs, Process, Outputs, and Customers	19
SMED	Single-Minute Exchange of Dies	66
TBM	Tire Building Machine	18
TKH	Twentsche Kabel Holding Group	1
TOC	Theory of Constraints	64
TOS	Table of Sin	84
TRIFR	Total Recordable Injury Frequency Rate	21
UNVA	Unnecessary Non-Value-Adding	28
VA	Value-Adding	28
VMI	Veluwse Machine Industrie Group	1
VOB	Voice of Business	19
VSM	Value Stream Map	41
WIP	Work in Process	24

1 Introduction

The first chapter introduces the research performed at the VMI Group to complete my Master's degree in Industrial Engineering and Management, and it is organised as follows. Section 1.1 introduces the company, the VMI Group. Subsequently, Section 1.2 explains the motivation for this research. Section 1.3 describes the problem context. Then, Section 1.4 describes the research goal and scopes the research. Section 1.5 introduces the research questions and outlines the research approach. Afterwards, Section 1.6 describes the deliverables. Finally, Section 1.7 outlines this research.

1.1 Company description

The Veluwse Machine Industrie Group (VMI) is part of the Twentsche Kabel Holding Group (TKH). TKH is an internationally operating organisation focused on high-quality, innovative technologies in high-growth markets. It is a listed company with its headquarters in Haaksbergen, the Netherlands. TKH employs about 6000 people and is active in the business segments of telecom, building, and industrial solutions. The industrial solutions segment consists of connectivity and manufacturing systems. VMI is a subsidiary in manufacturing systems, which contributed approximately 37% to the annual turnover of TKH in 2019 (TKH Group, 2020).

VMI, established in 1945, initially helped to rebuild the Dutch railways after the Second World War. In the early 1960s, the company entered the rubber and tire industry and became a machine manufacturer. Nowadays, VMI has grown into a market leader in machine manufacturing. It specialises in the tire, rubber, can, and care industry. It employs about 1600 employees worldwide. In addition to its headquarters in Epe, where about 900 people work, VMI is active in Brazil, China, Germany, Malaysia, Poland, Russia, Thailand, and the United States of America. The company has three manufacturing locations, located in Epe (the Netherlands), Leszno (Poland), and Yantai (China) (VMI Group, 2018).

The mission of VMI is to make its customers more successful through innovative technology. It continuously strives to bring its industries to the next level by providing state-of-the-art, innovative solutions, competitive cost of ownership, and excellent services (VMI Group, 2018).

We conduct this research at the Production Engineering department in Epe. Production Engineering focuses on the continuous improvement of production processes and is part of Production. Besides Production Engineering, Production consists of Assembly and Fabrication, Electrical Assembly, and Module Testing. Figure 1.1 represents the organisational structure of VMI in Epe. Production Engineering is framed red in the organisational structure.

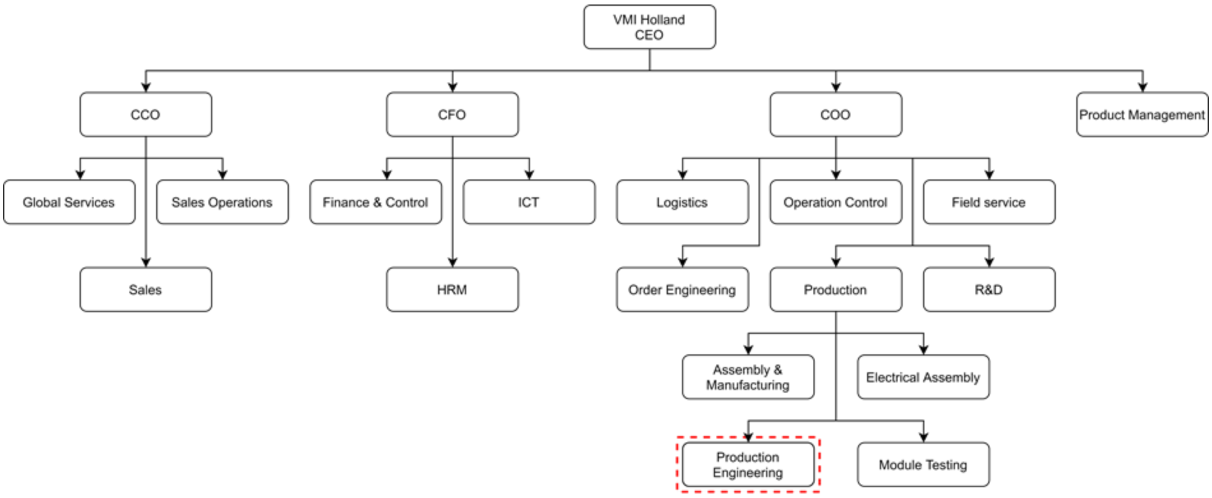

Figure 1.1: Organisational structure of VMI in Epe.

1.2 Research motivation

VMI subdivides its machines into modules and sub-modules. The manufacturing location of these modules depends on what kind of module it is. In Yantai and Leszno, the focus is more on the manufacturing of high-volume, low-variety modules. While in Epe, the introduction of new product developments and integral machine testing are relevant. Furthermore, the assembly of modules with intellectual property (IP) is in Epe. VMI allows, by its policy, the assembly of these IP modules only to be in Epe. These IP modules range from low-volume, high-variety to high-volume, low-variety.

The production group E720 currently assembles products related to the high-volume, low-variety IP modules. The activities it carries out are predominantly mechanical assembly. The production group E720 consists of employees of the sheltered workshop. A sheltered workshop accommodates people with a distance to the labour market. The Participation Act of 2015 supports the reintegration of these people. For instance, public employers with 25 employees or more must have a percentage of the jobs filled by people with a distance to the labour market (Ministerie van Sociale Zaken en Werkgelegenheid, 2020). Also, non-public organisations act more corporate socially responsible and employ these people. VMI considers corporate social responsibility particularly important and has dedicated two production groups as sheltered workshops. Production group E720 is one of them. The products it assembles characterise as relatively simple. Some examples of these products are the canister, lever, and pallet, given in Figure 1.2.

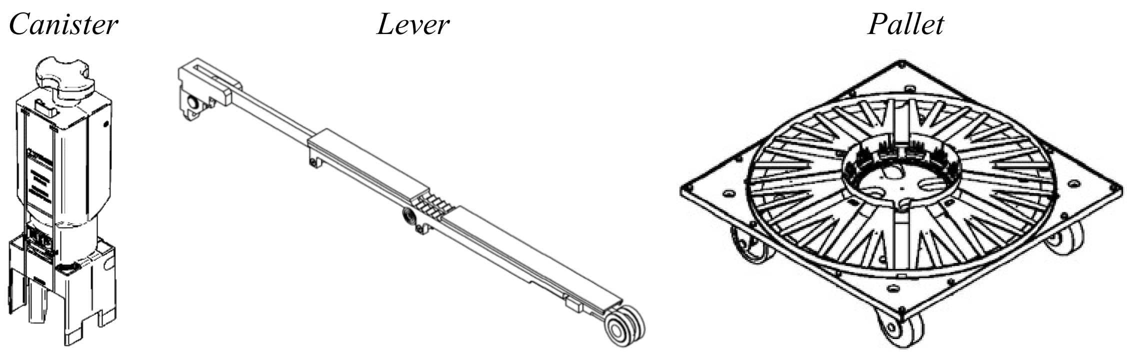

Figure 1.2: Overview of some products assembled by the production group E720.

In recent years, the total annual production hours and production quantity of the production group E720 increased. Figure 1.3 and Figure 1.4 show the production hours and production quantity per year from 2016 to 2020, respectively. In 2020, VMI experienced disappointing sales figures. These affected the operating results of the production group as well. The primary cause of these disappointing sales figures is the COVID-19 situation. However, the expectation is that the operating results will recover to previous levels in the short term.

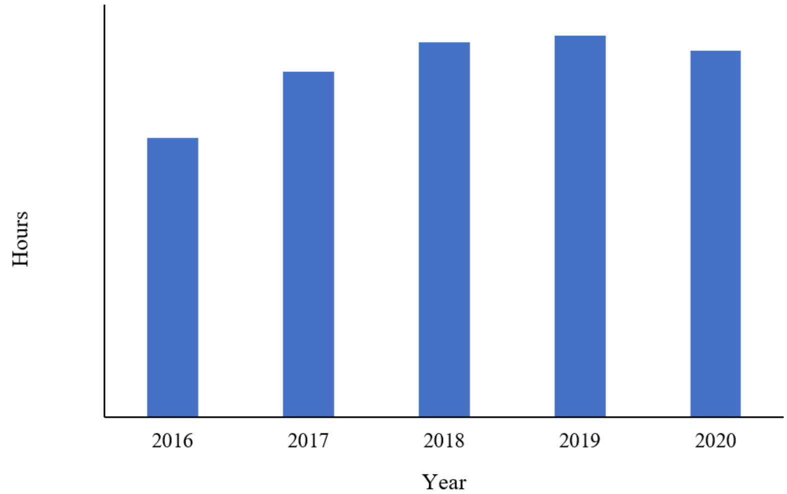

Figure 1.3: Total production hours of production group E720 over the years.

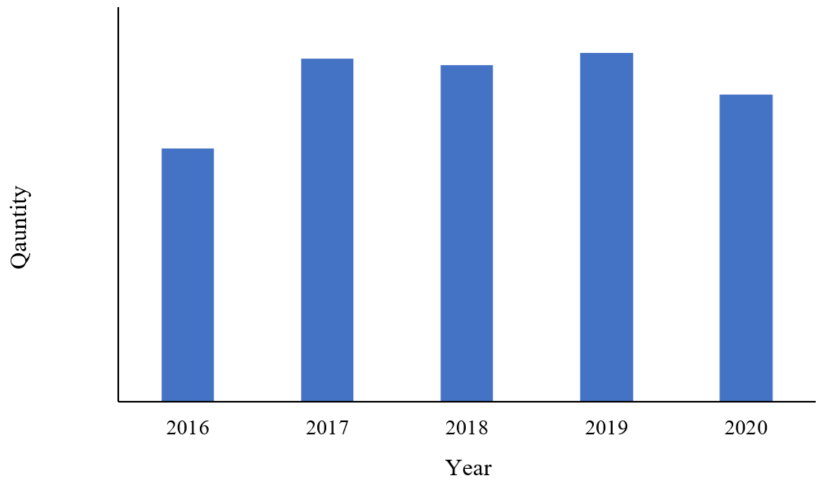

Figure 1.4: Total production quantity of production group E720 over the years.

Although the decision to produce IP modules in Epe is strategic, the production costs of these modules are also relevant. Production management considers it more important for the sheltered workshop than other production groups. They would like to produce at minimum costs and simultaneously act corporate socially responsible. It means the production processes are well structured, work and cost-efficient, repetitive in nature, and work pleasantly for the employees. However, the increase in production quantities clarified some activities could be more efficient. Also, the employees indicate that certain activities sometimes hinder them from working pleasantly. As a result, productivity is at a lower level, and the production hours and costs are higher. Therefore, production management desires to improve productivity by increasing the annual capacity of production group E720. Realising high capacity production processes while the number of employees remains intact also prepares the production group for the future. In the (near) future, production management plans to expand the product portfolio, which will increase the annual number of production hours.

1.3 Problem context

The previous section outlined the first issues currently at play. To describe the entire problem context, we use a problem cluster. A problem cluster depicts the causal relations between the problems. It helps bring order to the problem context and helps identify the core problem(s). A core problem is a root cause of the central, observed problem. The potential core problems are the problems that have no direct cause themselves. However, if the potential core problem is not influenceable, it cannot be a core problem (Heerkens & van Winden, 2017). The central problem in this research is the increase in production hours due to reduced productivity and increased workload. It is marked green in the problem cluster, Figure 1.5. In the problem cluster, we numbered the problems. The following paragraphs describe every problem.

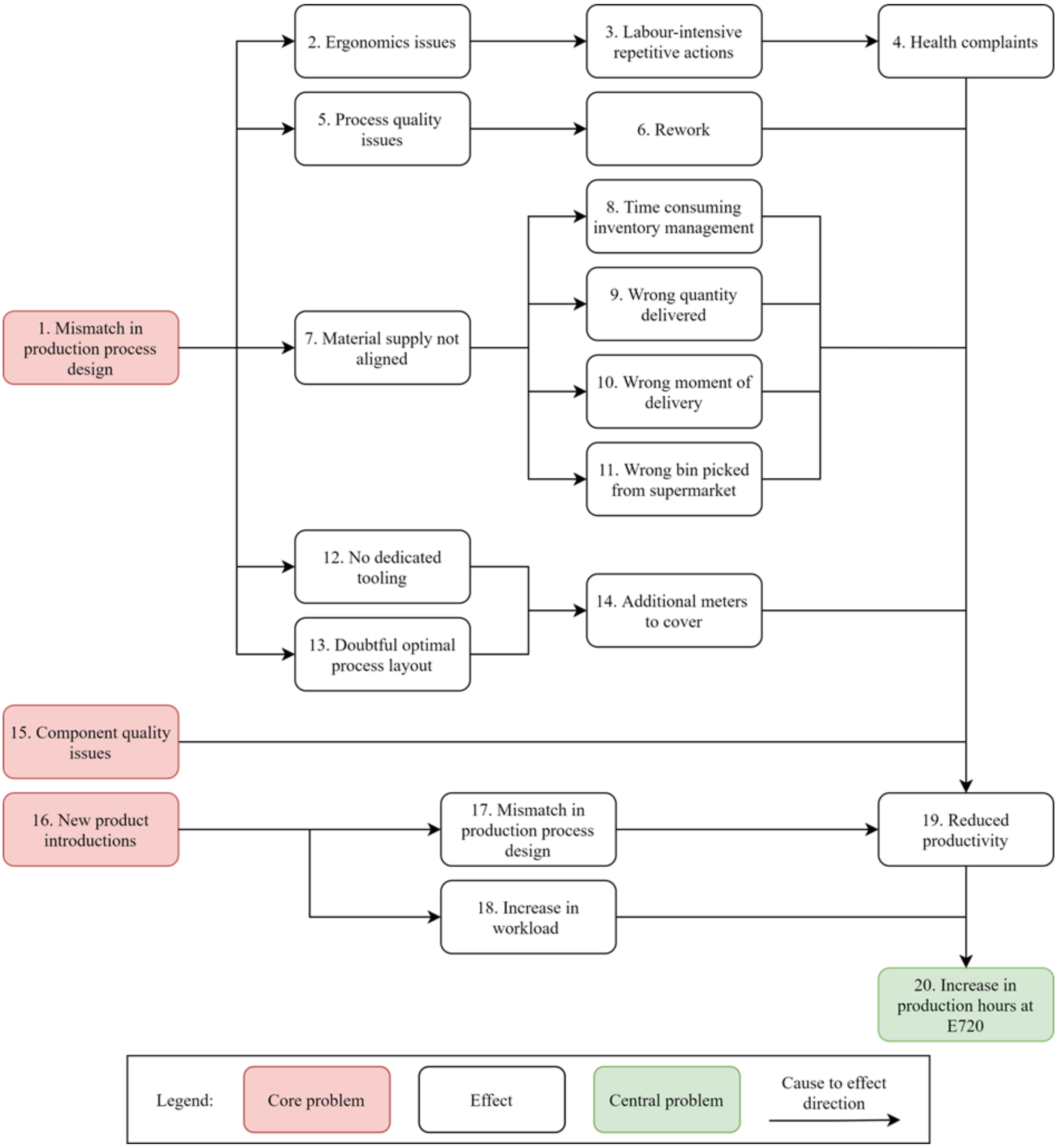

Figure 1.5: Problem cluster of production group E720.

The increased annual production quantity partly causes the hindrance in working pleasantly. Employees frequently perform activities such as the manual pressing of small components and tightening bolts with a torque wrench. Occasionally performing such a task is not experienced as a problem by the employees. However, when done repetitively throughout the day, the employees experience it as labour-intensive (3). The cause of these experiences is poor ergonomics (2). It causes health complaints (4), which reduce employee productivity.

The manual pressing of components has another consequence. During pressing, the force employees apply is not controlled, and not all employees are of equal strength. The result is varying pressing force. If the force is too great, it can lead to a quality issue. The variation in pressing force is one of the current process quality issues (5). The production group standardly applies the four-eyes principle to identify faulty products. It means that every finished product is checked for defects by another employee. The rejected products are either repaired or collected for dismantling. Repair, and especially dismantling, are time and labour-intensive processes. Hence, rework (6) reduces the productivity of the production group E720.

The alignment of material supply with the production processes also causes problems (7). In the production area of E720 are shelf racks representing supermarkets. One sheltered workshop employee regularly determines the inventory levels. If the inventory of a component or kit is below the reorder point, the supervisor of production group E720 orders it from the warehouse. The warehouse supplies a predetermined quantity of the component or kit within several days. The same sheltered workshop employee places the bins at their corresponding location. However, this way of inventory management is impractical and time-consuming (8). The employee spends a relatively large number of hours determining inventory levels and storing bins. In addition, the warehouse sometimes delivers the wrong quantity of a product (9) or supplies replenishment orders too late (10). Although the consequences are often minor, it still causes disruptions in the production schedule and a productivity loss. Finally, when the employees start with a new production order, they receive a list with the component number(s) or kit number(s). They match the numbers with the bins in the supermarket and collect them. For the employees, this is sometimes difficult. They occasionally collect the wrong bin (11) and have to return to the shelf rack to pick the correct one. The four described points of the material supply reduce the productivity of the production group. Therefore, the supervisor of production group E720 desires to align the material supply better.

Furthermore, product assembly is currently in batches since some production activities have no dedicated tooling (12). Although employees do not have to wait on each other, there is still a loss of productivity. They walk additional meters to complete their (sub)assembly (14). Also, the supervisor of the production group questions whether the current facility layout is optimal (13). A non-optimal layout results in additional walking meters for the employees (14) and thus reduces productivity.

The mismatch between the production process design and the product characteristics is the cause of the previously mentioned problems (1). One of the most relevant product characteristics is the annual production quantity. In recent years, the production processes have not evolved with the production quantities. They received little attention and are not that suitable for the annual production quantities. The reduced productivity (19) and increased workload cause an increase in the working hours at the production group E720 (20).

Moreover, the purchased components cause quality issues (15). For example, they are not according to specification or have transport damage. These components are logged as a non-conforming product (NCP) by VMI. An NCP means the employee(s) halted the production process and notified their supervisor of a quality issue. The effect of a quality issue differs and thus the loss in productivity. However, the number of NCPs within production group E720 is small. The production group reported in 2019 a little over one per cent and in 2020 less than one per cent of the total number of NCPs within VMI, as Table A.1 of Appendix A lists.

Finally, new product introductions (NPIs) will likely add additional products to the production group (16). The canister is an example, its transfer to the production group E720 is in the short term. Currently, the employees are in the process of learning how they can assemble these canisters independently. The employee supervising this process is the only other employee within VMI who can assemble these canisters. The assembly rate of this employee is canisters per hour. However, this rate is not representative rate for the sheltered workshop employees. It has yet to be determined, but an initial estimation is canisters per hour. Given the maximum number of 1600 canisters per machine (the), the workload can increase considerably with a modest number of sold (18). In case the number of annually sold is , an overestimation for the coming years, the assembly of canisters will add about % to the annual production hours at production group E720. In addition, a part of the NPI process is the development of the production processes. This development considers, among others, the location of manufacturing (e.g., Yantai), an estimate of the production quantities, and a budget. However, a mismatch between the product characteristics and the production process is realistic (17). The production process of the canisters is not designed for a substantial number of sold annually. The consequence is an additional loss of productivity (19). Thus, the increase in workload and potential loss of productivity increase the production hours at the production group E720 (20).

The increase in production hours due to reduced productivity and increased workload is the central problem in this research. The potential core problems are the mismatch of the production process design, component quality issues, and NPIs. All the potential core problems are influenceable and thus core problems. They are marked red in the problem cluster, Figure 1.5. However, the research focuses on improving the production process design and matching it with the product characteristics. The component quality issues are a minor cause. Only a negligible percentage of NCPs originate from production group E720. The overestimation of sold annually will considerably add production hours to the production group. However, the current situation, the mismatch in process design, causes additional production hours of far greater size than the future perspective will in the coming years. So, improving the production process design is a logical decision. The improvement potential of the process design is the highest in the short term. However, we do not entirely exclude the future perspective since the research findings may also apply to the NPIs in the long term.

Based on the decision to improve the production process design, it is possible to formulate an action problem. An action problem is a discrepancy between the norm and the reality as perceived by the problem owner. Action problems express both the norm and reality in terms of variables (Heerkens & van Winden, 2017). The action problem is that the design of the production processes does not match the product characteristics. The owner of this problem is VMI. The discrepancy between norm and reality is that the production process capacities are too low. However, there is no pre-defined norm in terms of capacity per production process.

1.4 Research objective

Given the discrepancy in the capacity of the production processes, the focus is on the following research objective:

Redesign the production processes[1] of production group E720 such that they increase in annual production capacity while the number of employees remains intact.

As this is a broad research goal, the scope of the research is as follows.

Production processes
The production group E720 assembles a substantial number of products. The focus is on one product and its production process to keep the research manageable. The selection of one product is part of mapping the current situation. The main selection criteria are the annual production quantity and production hours.

Toy problem
We consider the selected production process a toy problem for the other production processes of the production group. A toy problem breaks a large problem down into many smaller problems and intends to illustrate or exercise various methodologies (Russell & Norvig, 2016). In this research, we intend to apply various methodologies to realise a considerable capacity increase. If they result in a viable new production process design, the pilot process, then the other production processes can use the same methodologies.

Product
The products are not subject to major design changes. The form and function remain the same. The considered design changes, for example, improve the ease of assembly. However, if a significant design improvement is considered value-adding, we recommend it.

Component quality
We do not consider the component quality. The problem context, Section 1.3, mentioned that the number of NCPs at production group E720 is about one per cent of the total number of NCPs within VMI. The quality issues with purchased components are thus considered negligible. However, we do consider the process quality.

Facility layout
The facility layout consists of two aspects. The first and most important aspect is the production process layout of the selected product. The second aspect focuses on the overall facility, the production process within the facility.

Material supply
The material supply includes the components up to and including the finished product. The starting point for the components is how the warehouse supplies them to the production group. We do not consider the actual component delivery and collection of finished products as parts of the material supply. However, we consider, for example, the transport carriers, unit loads, use of kits, and packing of finished products, parts of the material supply.

Ergonomics
When improving the ergonomics, the focus is on finding a (technical) solution that prevents risk(s). Risk reduction occurs when avoidance proves impossible.

[1] The term production process is used throughout the research. It is an umbrella term for the facility layout and supply of information and materials.

1.5 Research design

Given the research scope in Section 1.4, the main research question is as follows:

How can a specific pilot production process of production group E720 be redesigned such that the annual production capacity increases considerably while the number of employees remains intact?

The research questions to answer the main research question are as follows.

Research question 1: What is the current situation at the production group E720?

1.1 What is the current facility layout?
1.2 What products does the production group produce?
1.3 Which product should be selected for production process redesign?
1.4 How is the current production process of the selected product organised?
1.5 What are the production processes characteristics of the selected product?
1.6 How is the material supply of the selected product organised?
1.7 What is the layout of the selected production process?

Answering research question 1 increases the understanding of the context and gains insight into the current situation. The current situation starts with mapping the facility layout and the product portfolio of production group E720. Furthermore, it includes the annual number of production hours and quantities per product. The enterprise resource planning (ERP) system of VMI provides this data. The product selection uses this data to compare the products and to come to a substantiated choice. Moreover, the current situation includes a detailed mapping of the production process of the selected product. Other relevant aspects of this process description are the material supply, process layout, and process characteristics. This data is collected using internal documents, interviews, observations, and working in the production process.

Research question 2: What is the current performance of the selected production process at production group E720?

2.1 What performance measures are currently in place?
2.2 Which performance measure(s) should be used to measure the performance?
2.3 How and how often should performance be measured?
2.4 How is the ergonomics currently quantified?
2.5 What is the current performance of the selected production process?

The current performance of the production process is a key starting point of the research. First, we determine the current performance measures VMI uses. Then, a data collection plan proposes how and how often we should measure so that we ensure we obtain reliable data. It also describes the current method VMI uses to quantify ergonomics. Finally, we determine the current performance of the selected production process and define it as baseline performance.

Research question 3: What factors influence the current performance of the selected production process at production group E720?

3.1 Which tools should be used to analyse the performance of the selected process?
3.2 What factors influence the performance of the selected production process?
3.3 Which influence factors should be selected?
3.4 What are the main focus points for process improvement?

Research question 3 focuses on identifying factors that influence the current performance of the production process. First, we determine and select suitable tools to analyse the performance. After applying the selected analysis tools, we should have identified a list of potential causes. Then, we score these influence factors to determine the impact these factors have on the performance of the selected production process. Afterwards, we select a number of these influence factors in line with the research objective. After the influencing factor selection, we determine the main focus points for improvement of the selected production process. Hence, we can review the literature for possible solutions more specifically.

Research question 4: What literature is available that relates to the main research question?

- 4.1 How should an assembly process be designed?
- 4.2 What alternatives do the literature provide for designing the facility layout?
- 4.3 What alternatives do the literature provide for organising the material supply?
- 4.4 What alternatives do the literature provide for improving ergonomics?
- 4.5 What does the literature provide about assembly processes in sheltered workshops?

The literature can provide knowledge and insights into frameworks, methods, principles, and techniques to identify potential alternatives. First, the focus is on a framework and principles for designing an assembly process. Furthermore, it involves research into a type of production process that matches the product characteristics. Then, alternatives for organising the material supply, designing the facility layout, and improving the ergonomics are studied. Lastly, in the literature, principles for assembly processes in sheltered workshops are reviewed.

Research question 5: Which design is best suited for the selected production process of production group E720?

- 5.1 What are the requirements of VMI for the new production process design?
- 5.2 What are feasible alternatives for the ergonomics, facility layout, and material supply based on the literature review?
- 5.3 Which alternative for the ergonomics, facility layout, and material supply best suit the new production process design?
- 5.4 What does the new design of the production process look like?
- 5.5 How should the design be aligned to co-operate with the sheltered workshop?

A new design of the production process starts with listing the requirements of VMI. These requirements evaluate the feasible alternatives. These alternatives include, for example, ergonomics, facility layout, and material supply. After selecting the most suitable options, we develop the production process design in more detail. The final step is aligning the new production process with the sheltered workshop. Alignment is such that the employees can work efficiently with the production process design. The literature review (research question 4.5) and the supervisor of the production group provide best practices.

Research question 6: What is the expected performance of the new production process?

- 6.1 How can the new production process design be verified?
- 6.2 What scenario(s) should be evaluated?
- 6.3 How and how often should performance be measured?
- 6.4 What is the performance of the new production process design?

Research question 6 determines the expected future performance of the new production process design. It starts by defining an approach to experiment with the new design using the literature. Then, we determine the scenario(s) to evaluate, and we create a data collection plan. The latter outlines how and how often we should measure such that we ensure we obtain reliable data. The data collection plan uses the same performance measures as determined in research question 2.2. After determining the future performance, we compare it with the current performance of the selected production process. Finally, we discuss the technical viability of the new process design.

Research question 7: How should the new production process design be implemented?

- 7.1 What activities should be carried out to implement the new production process design?
- 7.2 How should the activities be carried out, and who is responsible for which activity?
- 7.3 To what extent is the new production process design financially viable?

Implementation of the new production process design at the production group E720 is the final part of the research. Provided that the new process design is technically viable, we list and describe the activities to carry out in an implementation plan. The implementation plan phases the implementation and identifies those responsible for the activities. We may review the literature in the case when essential knowledge of, for example, change management is missing. Lastly, we determine the financial viability of the new production process design by evaluating the costs of implementation and the expected benefits of improved production performance.

Research framework

The research questions form the research approach to answer the main research question. As a framework, we use DMAIC. It is an abbreviation of define, measure, analyse, improve, and control. DMAIC is a data-driven improvement cycle used to improve, optimise, and stabilise business processes and products. It is structured and standardised, and decisions are fact-based or statistically based (Theisens, 2017). DMAIC suits our research since the research questions cover every phase of the framework. However, we do not fully perform the control phase. It controls all improvements to ensure sustainable process improvement. Our research ends after drafting the implementation plan. Figure 1.6 outlines the research approach schematically and places them in the DMAIC framework, where the dashed lines indicate the needed input.

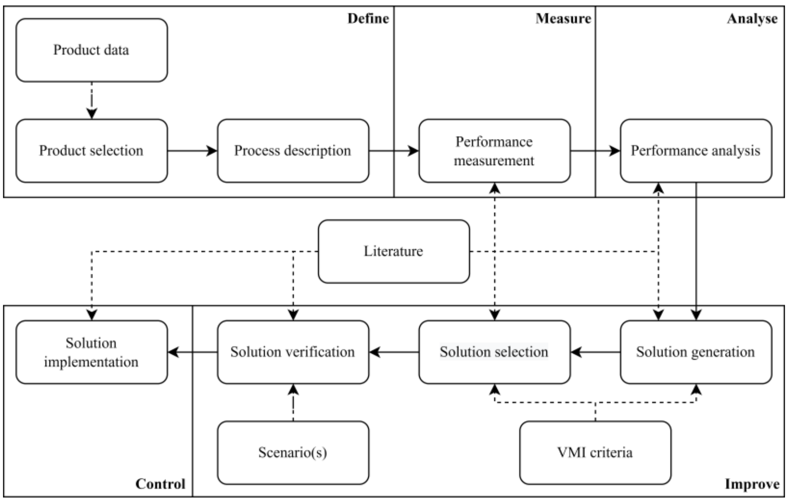

Figure 1.6: Schematic overview research approach placed in the DMAIC framework.

1.6 Deliverables

The research results in the following deliverables:

- An improved design of the selected production process of production group E720.
- An implementation plan for the selected production process design.
- A framework to design the other production processes of production group E720.

1.7 Thesis outline

The remainder of this research is organised as follows. Chapter 2 selects a product and describes its current situation of the product. Then, Chapter 3 determines the current performance of the selected production process. Chapter 4 analyses this performance and identifies the main influence factors. Subsequently, Chapter 5 covers the literature review. Chapter 6 develops a new production process design. Afterwards, Chapter 7 determines the expected future performance of the new process design. Chapter 8 describes the implementation plan. Finally, Chapter 9 covers the conclusions and recommendations.

2 Current situation

The second chapter describes the current situation at production group E720 and is organised as follows. Section 2.1 introduces the sheltered workshop. Then, Section 2.2 outlines the facility layout of the sheltered workshop. Section 2.3 presents the product portfolio of production group E720. Subsequently, Section 2.4 describes the process of selecting one product from the portfolio. Section 2.5 details the selected product, its production process, material supply, and facility layout. Afterwards, Section 2.6 finalises the chapter by summarising the main findings.

2.1 Sheltered workshop

The sheltered workshop of VMI originates from corporate social responsibility. It consists of the production groups E720 and E763, and it performs high-volume, low-variety electrical (E763) and mechanical assemblies (E720). The sheltered workshop accommodates people with a distance to the labour market, mainly people with cognitive disabilities. To support the employees during working activities, they receive additional guidance from their supervisor and have adapted workplaces. These adapted workplaces should provide the desired production processes that are well structured, work and cost-efficient, repetitive in nature, and work pleasantly for the employees. The sheltered workshop thus offers its employees the opportunity to do work that they would not normally be able to do. Furthermore, the employees learn new skills and have a social network. It structures their life and makes them feel useful.

2.2 Facility layout

The manufacturing location of VMI in Epe consists of several production facilities. Hall 5A houses the sheltered workshop of VMI and thus consists of the production groups E720 and E763. The main corridor separates the production groups, as Figure 2.1 illustrates. Tugger trains use it for the material supply and collection of finished products. The I/O areas in the facility layout are the inbound and outbound storage locations for materials. The materials used in high quantities are stored in shelf racks and a pallet rack, where the pallet rack is for materials of larger dimensions.

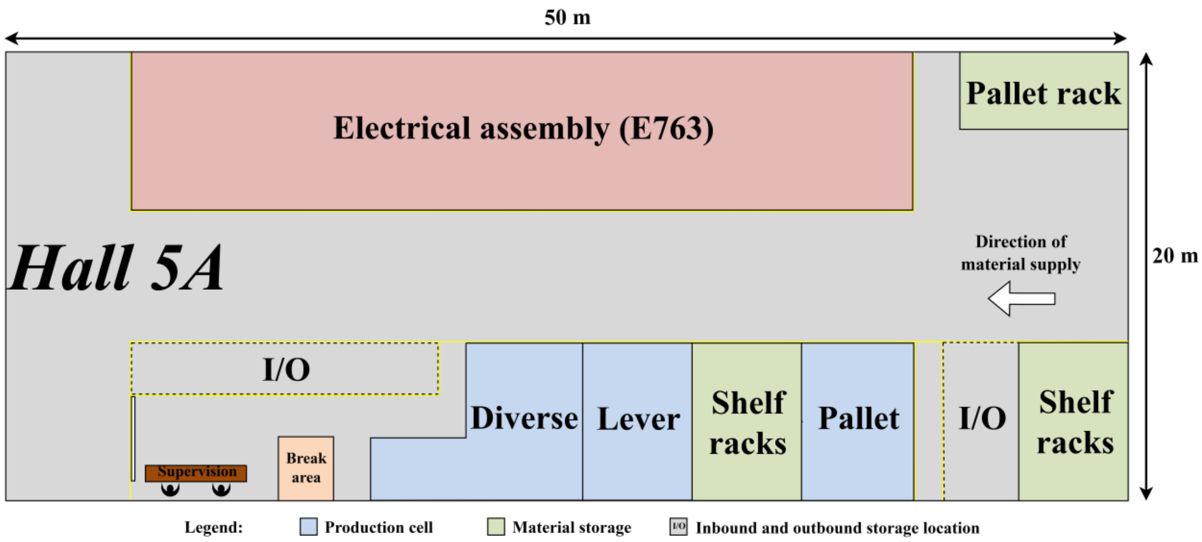

Figure 2.1: Facility layout of the sheltered workshop of VMI in hall 5A.

The facility layout has three assembly cells, marked blue in Figure 2.1. The product families lever and pallet each have a dedicated production cell. Employees use the third cell for various other product families and support activities, listed in Section 2.3. The fixtures, tooling, and tools used for assembling the product varieties are grouped in the production cells. Although the two dedicated production cells have reduced setup times, the cells are idle when there is no product demand. They do not offer the flexibility to assemble other product families.

2.3 Product portfolio

The canister, lever, and pallet are the first three products that we mentioned the production group E720 assembles. The product portfolio of the production group consists of ten product families in total. They relate mainly to the high-volume, low-variety IP modules. In addition, the employees perform support activities for other production groups and service engineers. Fifteen categories subdivide the activities of the production group, where ten are the product families and five are support activities. Figure 2.2 lists and illustrates the ten product categories. The five support activities are field service, hour cards, tooling, WOP, and others. Appendix B provides a general description (e.g., application and function) of these 15 categories.

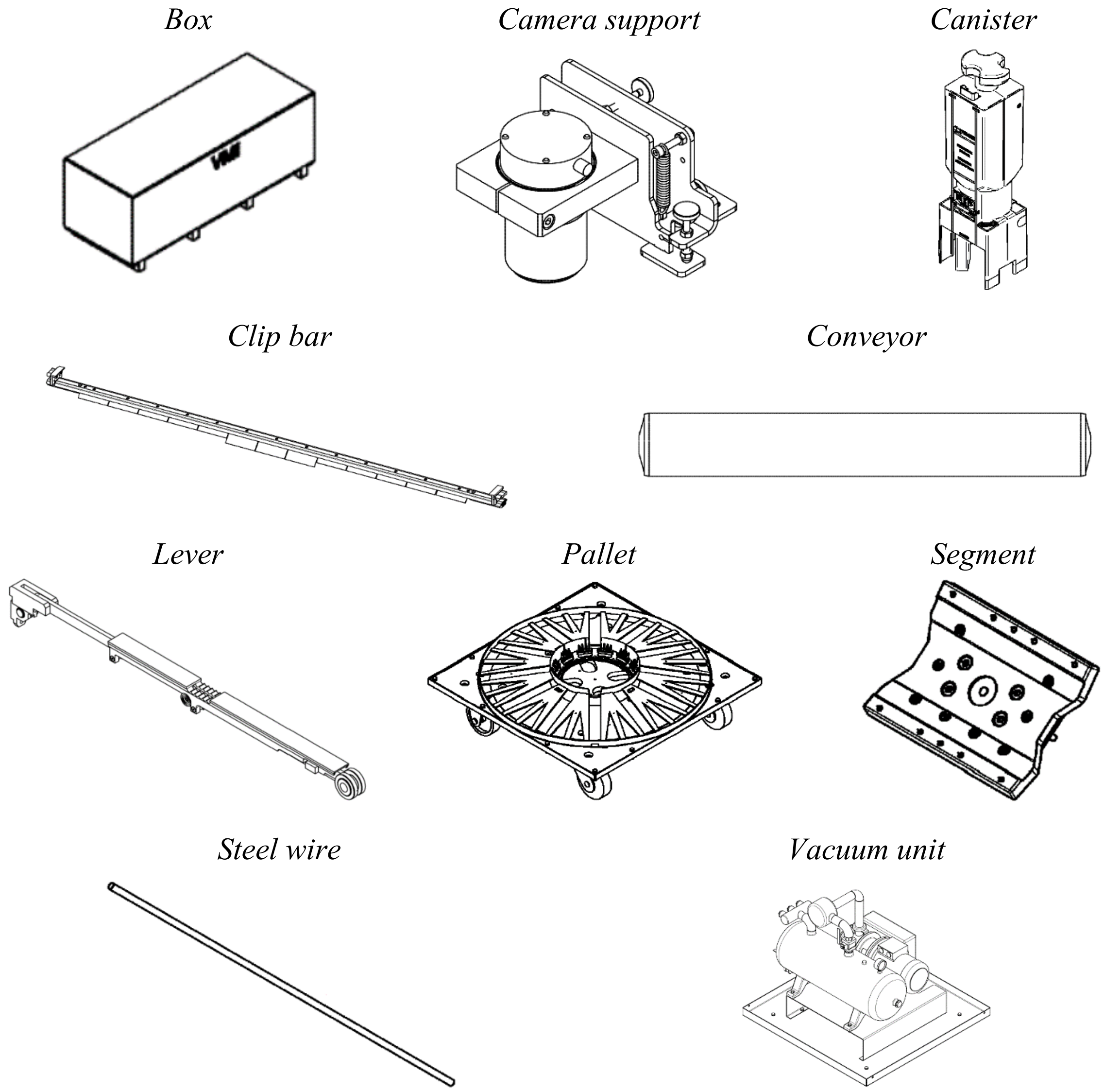

Figure 2.2: Overview of the product portfolio of production group E720.

2.4 Product selection

The product portfolio listed ten product families production group E720 assembles. Recall from Section 1.4 that the research focuses on one production process to exercise various methodologies: the toy problem. Therefore, we select one of the ten product families in a product selection. The product selection uses a three-step approach, which is as follows. Subsection 2.4.1 places the ten products in the perspectives of growth and potential. Subsequently, subsection 2.4.2 determines and uses a threshold value to exclude products with a small share in the total number of production hours. Finally, subsection 2.4.3 compares the remaining products in terms of the annual production hours and quantities. Furthermore, it selects the product for a new production process design.

2.4.1 Growth-share matrix product portfolio

The product selection process starts by putting the product portfolio in the perspectives of growth and potential. Henderson (1970) of the Boston Consultancy Group proposed an approach for such a portfolio analysis. It is the best-known and most widely used approach. It uses a two-dimensional matrix, where the industry growth rate is on the vertical axis, and relative market share is on the horizontal axis. Circles in the matrix represent the products, where the circle size corresponds to the product revenue within the organisation (Marcus & van Dam, 2015). Henderson (1970) divided the growth-share matrix into four quadrants, each of which represents a particular type of business:

- Question marks. Products in high growth markets and low relative market share.
- Stars. The growth market and market share are both high for the product.
- Cash cows. Products in low growth markets and high relative market share.
- Dogs. The growth market and market share are both low for the product.

Approach growth-share matrix for portfolio analysis

Applying the growth-share matrix to the product portfolio of product group E720 requires new perspectives on the relative market share and growth rate of the industry. For example, determining the market share of a product requires its competitors' share of the market. However, the competitor perspective is lacking. The products do not directly compete for a market share since they are parts of modules in the machine. Therefore, we define the market share as the ratio a product has within the total number of production hours. For this purpose, we use the operating results of 2019 since the COVID-19 situation affected the operating results of 2020. We define the product growth rate as the difference in ratios a product has in the annual production hours between 2016 and 2019. If 2016 product data is absent, we use data from the first entry. It is important to note that the annual production hours already increased by more than a between 2016 and 2019, discussed in the research motivation, Section 1.2. Lastly, all products have equal circle sizes since they do not generate direct revenue. They are parts of machine modules. Figure 2.3 shows the growth-share matrix of the product portfolio of the production group E720, where the origin of the matrix is the averages of the product growth rate and product share.

High
Product growth rate
Low

Confidential

Low Relative market share High

Figure 2.3: Growth-share matrix of the product portfolio of production group E720.

Henderson (1970) stated that successful organisations have a product portfolio with different growth rates and market shares. An organisation can only use its strengths to capitalise on its growth opportunities when it has a balanced portfolio. A balanced portfolio consists of stars, cash cows, and question marks. Dogs are unnecessary. They are evidence of failure either to obtain a leading position in the growth phase or to get out and cut the losses. The growth-share matrix of Figure 2.3 classifies products as dogs. These are the . Usually, the advice would be to discontinue dogs. However, since they are parts of machines, discontinuation is not possible. However, from the perspective of product selection, we can exclude them. Their potential and growth are not attractive for a new production process design. We continue the product selection by defining a threshold value in the share of annual production hours. It allows excluding products that only have a small part of the production hours.

2.4.2 Threshold value

We base the threshold value on the research objective to increase the production capacity considerably. We express considerably for now as a % increase. Some simple algebra reveals that a % increase in production capacity equals a % decrease in production hours to obtain the same output as before capacity increased. For instance, if a process assembles products per hour and increases by % to products per hour, it would require minutes to assemble products. Thus, the reduction in assembly hours equals %. So, we need a product whose share in the annual production hours is at least % to achieve the research objective. Figure 2.4 shows a bubble plot of the production hours per product from 2016 to 2020, where the dotted line indicates the % threshold value in production hours per year. The bubble size is the share a product has in the annual number of production hours. The bubble plot shows that the do not exceed the threshold value. Although the growth-share matrix proved that they had a relatively high growth rate in recent years, they did not obtain a large enough share of the total number of production hours. In addition, the share the has reached within years is intriguing. It shows that it potentially can become a key product of the production group within several years. However, we exclude the together with as they do not exceed the % threshold value. The remaining products are hence the lever and pallet.

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Figure 2.4: Production hours per product compared to the % threshold value in production hours over the years. The bubble size is the share the product has in annual production hours.

2.4.3 Final selection

The product selection continues by comparing the lever and pallet in terms of the annual production quantity. For this purpose, a bubble plot of the production quantities for both products from 2016 to 2020 is in Figure 2.5. In the figure, the bubble size is the share the product has in the annual production quantity. Figure 2.5 indicates that the production group E720 assembles significantly more levers than pallets. The lever has a share over times larger than the pallets in the annual production quantity. Furthermore, Figure 2.4 and Figure 2.5 indicate that the productivity of the processes decreased in recent years since the assembly hours were not in proportion to the annual growth in production quantities. However, the lever has the largest share in production quantity and hours. Therefore, we select the lever as the product for production process redesign. The lever has the largest shares of any product in the product portfolio in the annual production quantity and hours. In addition, it has growth and potential since it is a in the growth-share matrix. In addition, the lever is a product related to an IP module. The latter means that the lever assembly will remain in Epe for years since it is part of a strategic module.

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Figure 2.5: Production quantity of the lever and pallet over the years. The bubble size is the share the product has in annual production quantity.

2.5 Product and process description lever

The product selection selected the lever as the production process to redesign. Therefore, this section elaborates on the product and its process. First, subsection 2.5.1 introduces the product design of the lever. Subsection 2.5.2 describes its production process. Subsequently, subsection 2.5.3 describes the material supply of the lever. Subsection 2.5.4 outlines the layout of the process.

2.5.1 Product design

VMI manufactures tyre building machines (TBMs) that build passenger or truck tyres. Both machine types use levers in the tyre building process. These levers fulfil the same main function of rolling the layers of rubber around the tyre beads. However, there are some fundamental differences. After obtaining a better understanding of the lever varieties, it became clear that the levers used for building truck tyres have a different design and assembly process. In addition, these levers, called shoulder levers, accounted for approximately to % of the annual production quantity and hours within the levers. If we re-evaluated the product selection, it would not change the outcome. The total production quantity and the number of production hours are still the highest of any product in the product portfolio. Also, it remains a product with growth and potential since it is still a in the growth-share matrix. Therefore, we exclude the shoulders levers as the research focuses on one pilot production process, considered a toy problem. Hence, the remainder of the research focuses on the levers used for building passenger tyres, referred to as levers.

The inch size of the rim and the tyre's height from the rim define the lever to use in the TBM. Based on these two properties, a subdivision of the levers results in six categories, shown in Table 2.1. To clarify the naming of, for example, 12"-13"-L398.5, the '12"-13"-' represents the inch size range, and 'L398.5' is the centre-to-centre distance between the pivot point and rolls. As mentioned, the rolls, mounted on the tip of the lever, roll layers of rubber around the tyre beads during tyre building. At a more detailed level, we can distinguish per category different types. There are the standard and clip bar levers. The clip bar levers temporarily hold the clip bar when the applicator applies the first layer of rubber to the carcass drum. In the current TBM, the clip bar mechanically attaches to the levers, while in the previous model, the clip bar attaches to the levers by a vacuum. Between the models, the standard levers have not changed. Therefore, the vacuum levers are an after-sales service. The mechanical and vacuum variants are sets of two times three clip bar levers. The M and the V in Table 2.1 indicate that every lever category has a variety that can hold the clip bar mechanically or through a vacuum.

Table 2.1: Subdivision of the levers: standard levers (S), mechanical (M), and vacuum clip bar levers (V).

Category	Types			Category	Types		
12"-13"-L398.5	S	M	V	16"-18"-L395	S	M	V
14"-17"-L395	S	M	V	19"-20"-L413	S	M	V
14"-18"-L495	S	M	V	19"-24"-L493	S	M	V

An exploded view of a standard lever, where it also names the components, is given in Figure 2.6. Appendix C elaborates on the product design of the lever. It lists the components and component quantities in a standard and both clip bar levers. Furthermore, it identifies similarities and differences between the lever types. Finally, it visualises the standard and clip bar levers and gives a flowchart of the six standard levers.

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Figure 2.6: Exploded view of a standard lever.

2.5.2 Production process

Although every lever variety has its unique set of components, the assembly process is, in essence, the same. To outline key aspects of the lever production process and other supporting processes, we used a SIPOC. SIPOC is an abbreviation of suppliers, inputs, process, outputs, and customers. It is a high-level process description without any details (CSSC, 2018). In Appendix D, we elaborate on the approach used to create a SIPOC. However, it starts with determining the voice of the business (VOB), which is as follows: a well-functioning lever assembled pleasantly and efficiently within time and budget. The standard measures of VMI, the QLTCS, and ergonomics subdivide the VOB into critical to qualities (CTQs). QLTCS is an abbreviation of quality, lead time, technology, cost, and safety, and VMI uses them to monitor process performance. We excluded technology since VMI has not expressed it in a performance measure. Although ergonomics is not a standard measure and thus not actively measured, we added it as CTQ since its importance is stressed repeatedly by people concerned with the lever assembly process. The following five paragraphs discuss per CTQ the external and internal CTQs. Parts of the CTQ tree visually support these paragraphs, and Figure E.1 in Appendix E gives the entire CTQ tree.

Quality

The quality CTQ divides into surface appearance and smoothly operating. The first relates to the component quality and means that the components should not have any surface defects. The other external CTQ, smoothly operating, mentions the alignment of parts and assembled according to instructions as internal CTQs. The employees check these two internal CTQs with the four-eyes principle. Figure 2.7 shows the translation of the quality CTQ into the three internal CTQs and their corresponding specification.

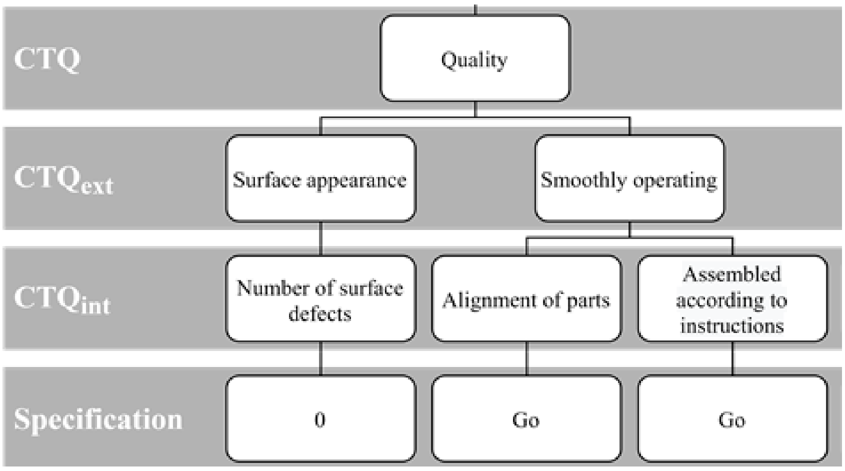

Figure 2.7: Translation of the quality CTQ into internal CTQs and their corresponding specification.

Lead time

The lead time lists the cycle and waiting time as external CTQs. The cycle time divides into value-adding and (un)necessary non-value-adding time. They are performance measures standardly but not actively used by VMI to measure process performance. The waiting time splits into product lateness and idle time of the components. Figure 2.8 gives the translation of the lead time CTQ into the internal CTQs and their corresponding specification.

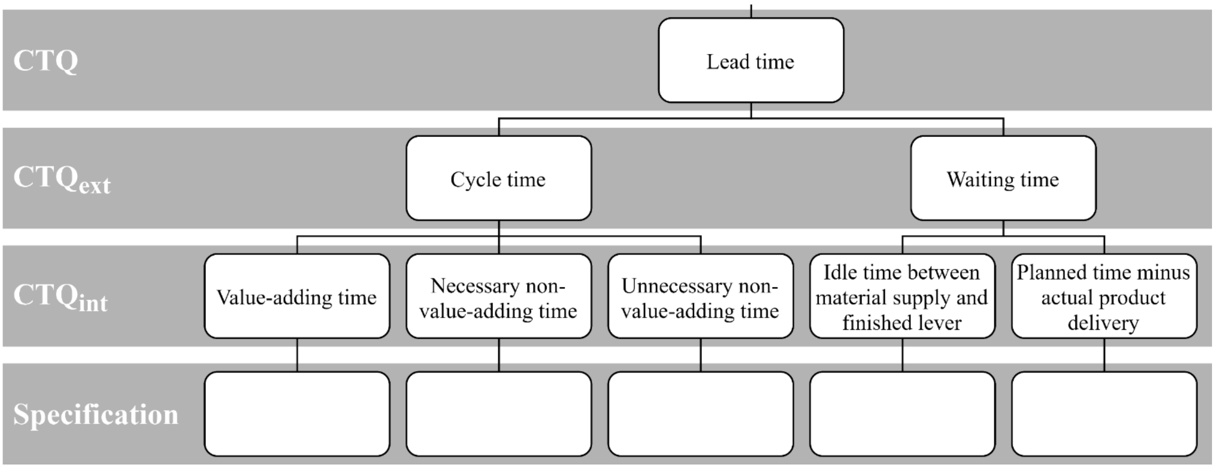

Figure 2.8: Translation of the lead time CTQ into internal CTQs and their corresponding specification.

Costs

The costs translate into the direct assembly costs, given in Figure 2.9. The direct assembly costs are cycle time per production order (PO) times the costs VMI incurs per hour. We did not specify the costs per lever since they differ per lever type. For example, the assembly of a standard lever generally takes less time than the assembly of a clip bar lever.

Safety

The safety CTQ mentions a risk inventory and evaluation (RI&E) as the external CTQ. In a RI&E, the employer records the health and safety risks of the work activities. In addition, the evaluation assesses the likelihood of occurrence, duration, and effect of a hazard on the employees. Employers in the Netherlands are obliged to have an up-to-date RI&E (Van der

Klauw, Kwantes, & Van Vliet, 2012). The external CTQ translates into the internal CTQs the lost time injury frequency rate (LITFR), total recordable injury frequency rate (TRIFR), and the number of (near) incidents. The LITFR is the number of recovery hours a worker needs before performing his or her regular working activities per million hours worked. The TRIFR is the lost time injury and injuries requiring treatment by a medical professional per million hours worked (OCIMF, 1997). Figure 2.9 lists the translation of the safety CTQ into the three internal CTQs and their corresponding specification. These specifications are targets VMI has set.

Ergonomics

The ergonomics translate into the physical workload that, in turn,, translates into the ergonomics score of the production process. The ergonomics score is the result of applying a suitable method to quantify ergonomics. Determining this method is part of the literature review. The threshold value for a production process with good ergonomics differs per method. For example, one method uses a three-colour scale, whereas another uses a ten-point rating scale. Therefore, the specification is left open, as Figure 2.9 shows.

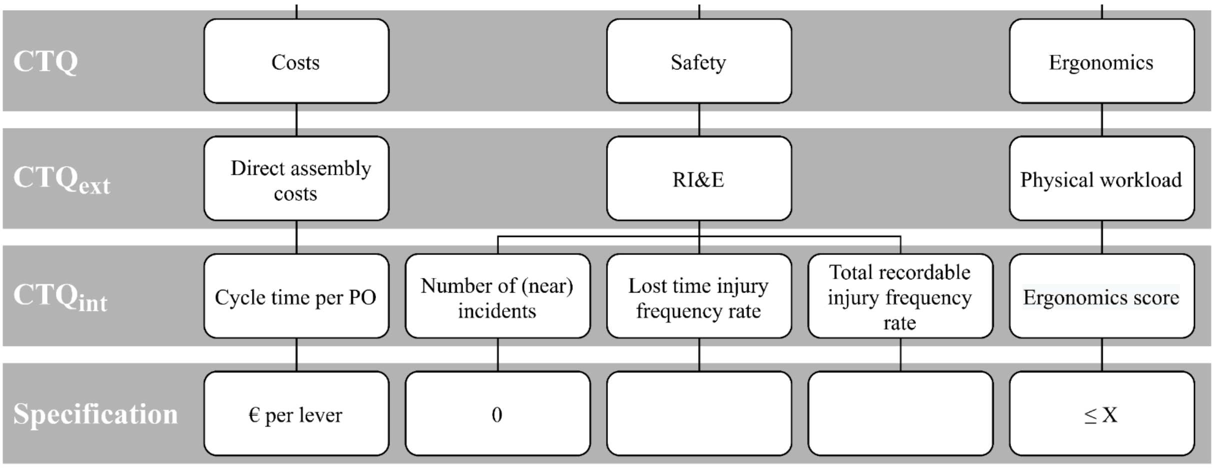

Figure 2.9: Translation of the costs, safety, and ergonomics CTQs into internal CTQs and their corresponding specification.

The process outputs and requirements in the SIPOC of the lever assembly process are the internal CTQs and their specifications of the CTQ tree. The SIPOC of the lever assembly process, shown in Figure 2.10, has departments of VMI as suppliers and customers, given the research scope Section 1.4. The warehouse supplies the materials together with prints of the handover list and POs. A handover list mentions the supplied materials quantities and expected delivery date in case of a shortage, whereas a PO provides general information such as the parts list. The latter allows the production group's supervisor to prioritise activities in the production schedule. For this purpose, the supervisor uses the different PO types. VMI distinguishes project-based and non-project-based parts, where the latter are also called anonymous parts. Anonymous parts can become project-based parts when they are assigned to a project (e.g., a new project or spare part). They are commonly used and act as a buffer for the high demand for the part. The PO prioritisation results in the employees first finishing spare part and new project POs before starting with anonymous POs. The customers of the finished levers are the drum workshop and the warehouse.

Suppliers	Inputs	Requirements	Type	Process	Outputs	Requirements	Customers
Warehouse	Materials	Correct quantity	C	Start	Lever	Number of assembled levers	Drum workshop
		On time delivery	C		Number of surface defects	0	Warehouse
		According to specifications	N		Alignment of parts	Go	
Warehouse	Handover list (printed)	Present	C		Assembled according to instructions	Go	
Warehouse	Production order (printed)	Present	C		Value-adding time		
Operations Control	Production information	Rough schedule	S		Necessary non-value-adding time		
Supervisor production group E720	Production schedule	Priority	S	Process	Unnecessary non-value-adding time	*Confidential*	
Work planning	Digital work instruction	Available	C		Idle time between material supply and finished lever		
					Planned time minus actual product delivery		
					Cycle time per PO	€ per PO	
					Number of near incidents	0	
					LTIFR	*Confidential*	
					TRIFR		
				End	Ergonomics score	≤ X	

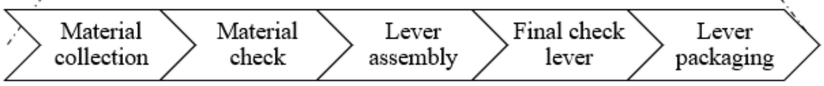

Figure 2.10: SIPOC of the lever production process.

Lever assembly process

The assembly of the lever is in five steps, schematically shown in Figure 2.11. It starts with glueing of bush bearings into the pivot block. Then, the employees press the ball bearings and rolls into the lever in the second and third steps, respectively. Afterwards, they join the lever base to the pivot block. The assembly ends with the mounting of the slide block resulting in a finished lever. After assembly, another employee performs a final check on the finished lever.

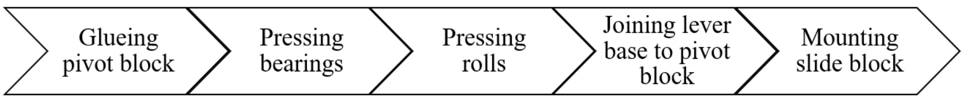

Figure 2.11: Schematic overview of the steps in the lever assembly.

Figure 2.12 visualises the lever assembly process with photos. Appendix F discusses in detail the activities per assembly step. The main points to mention about the assembly process are:

- The assembly is predominantly mechanical assembly.
- Two assembly steps use an adhesive to secure components.
- The employees use the same fixtures for every lever variety.
- The fixtures do not fixate or align the lever with the tooling.
- The employees perform a visual or functional check after every assembly step.
- The employees use a go or no-go gauge to check the bush bearings in the pivot block.

(1) (2) (3)

(4) (5) (6)

(7)

Figure 2.12: The lever assembly process in steps: glueing of the pivot block (1) and quality check using the go or no-go gauge (2), pressing the bearings (3), pressing the rolls (4), joining the lever base to the pivot block (5), and use of adhesive (6) for mounting the slide block (7).

2.5.3 Material supply

The master production schedule (MPS) assigns POs for levers per week to the production schedule. Furthermore, it controls the material supply by generating picking orders for the warehouse by comparing the theoretical inventory levels in the shelf racks with the POs for the next week. The warehouse receives an order if the component inventory level is below a certain level or insufficient to assemble the POs. The warehouse supplies a predetermined quantity of the component in bins. Tugger trains deliver the components to the production group, and an employee places the components at their corresponding location in the shelf racks. After the supervisor of the production group prioritised the activities and drafted a production schedule, employees are assigned to POs. The employees use the printed PO to collect the components for every assembly step. After assembly, they return the unused components to the shelf racks. The finished levers return to the warehouse, where spare part levers remain for shipment. The warehouse transports the other project-based and anonymous levers to the drum workshop.

2.5.4 Facility layout

The lever has a production cell within the facility layout of production group E720. The production cell has a functional layout to produce the levers in batches. It allows the employees to work on multiple POs at the same time. Figure 2.13 depicts that every assembly step has a dedicated location in the layout. The lever production cell consists of steel workbenches on which manual presses stand. Figure 2.14 shows the presses used for the second and third steps of the lever assembly. Also, there is a rubber mat to mute the noise of hammering the lever base to the pivot block. The employees perform the first four steps of the assembly process in the lever production cell. However, they mount the slide block to the lever and do the final check in the production cell used for various activities. Two workstations have the equipment needed to mount the slide block. Therefore, Figure 2.13 shows three workstations of the diverse production cell.

The two rows of blue blocks in Figure 2.13 are the shelf racks. They represent a supermarket. The supermarket, also shown in Figure 2.15, stores components, empty bins, rejected levers, and work in process (WIP). The empty bins were either used for storing components or finished levers. The WIP consists of bins filled with glued pivot blocks. They are, together with the components in the supermarket, anonymous parts. Finally, Figure 2.13 shows tool cabinets that store the fixture and tools used for the first and fourth assembly steps.

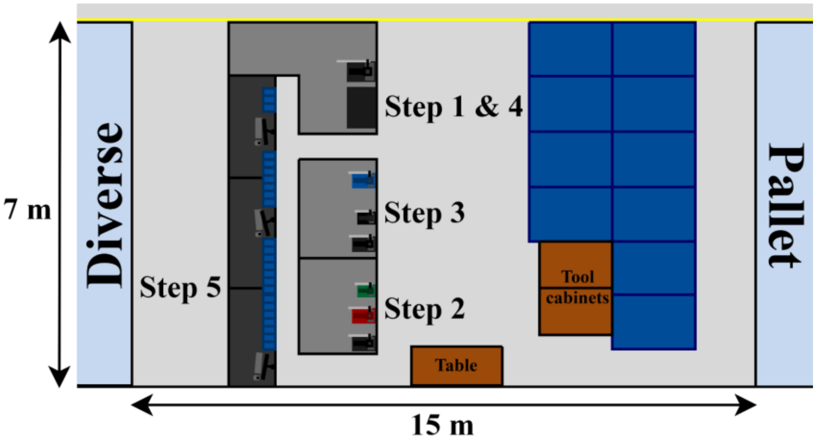

Figure 2.13: Facility layout of the lever production process.

Figure 2.14: Tooling used in the lever production process.

Figure 2.15: Shelf racks located next to lever production process.

2.6 Conclusion

The second chapter focused on providing insight into the current situation at the production group E720. The topics discussed introduced the sheltered workshop and its product portfolio and facility layout. Then, we selected a product, the lever, out of the product portfolio. Afterwards, we detailed the product design, production process, material supply, and facility layout of the lever. Hence, we answered the first research question: *"What is the current situation at production group E720?"*.

The sheltered workshop of VMI originates from corporate social responsibility. One of its production groups, production group E720, performs the mechanical assembly of high-volume, low variety products. Its product portfolio consists of ten product families and five categories of support activities. Two of these products (i.e., the lever and pallet) have a dedicated production cell in the facility layout. In addition, there is a third cell used for the other product assemblies and support activities. Furthermore, it has shelf racks to buffer and store components used in high quantities.

The product selection selected the lever for the production process redesign. It has growth and potential since it is a in the growth-share matrix. Also, the lever has in terms of production hours and quantities by far the largest share of any product in the product portfolio. Furthermore, the lever is an IP-related product. It means the assembly of levers will remain in Epe for years to come, given its strategic value. Finally, the productivity of the process decreased in recent years since the annual assembly hours were not in proportion to the annual growth in production quantities.

The inch size range and the working length of the lever subdivide the levers into six categories. In addition, there are standard levers and mechanical and vacuum clip bar levers per category. The shelf racks closest to the lever production cell store the components needed for the lever varieties. The MPS controls the supply of these materials and schedules the lever POs per week. The assembly of levers is in batches, generally 45 units for standard levers and five sets for clip bar levers. Assembly of the levers is a five-step process, first glueing the pivot blocks, second pressing the ball bearings, third pressing the rolls, fourth joining the lever base to the pivot block, and finally mounting the slide block. Every assembly step has a dedicated location in the production cell. Moreover, visual and functional inspections and the four-eyes principle ensure product quality. Besides quality-related requirements, VMI has also formulated requirements for the lever assembly in terms of lead time, costs, safety, and ergonomics.

The requirements and specifications in terms of quality, lead time, costs, safety, and ergonomics allow determining whether the production process of the lever meets these requirements. Therefore, the research continues in Chapter 3 by determining the current performance of the lever assembly process.

3 Current performance

The third chapter determines the current performance of the lever production process and is organised as follows. Section 3.1 describes the data collection plan. Then, Section 3.2 studies the validity of the measurement systems. Section 3.3 discusses the baseline performance of the lever production process. Section 3.4 finalises the chapter by summarising the main findings.

3.1 Data collection plan

The performance measurement of the lever assembly requires an approach to determine the current performance. Therefore, we create a data collection plan. The data collection plan first discusses the performance measures that currently are in place in subsection 3.1.1. Subsequently, subsection 3.1.2 introduces the measurement methods and frequency per KPI. It highlights work sampling, the measurement technique used for the performance measurement of the lead time KPIs. Subsection 3.1.3 gives priority numbers to the KPIs and selects the KPIs used for process measurement.

3.1.1 Key performance indicators

The CTQ tree in Figure E.1 in Appendix E translated the VOB into 13 internal CTQs. These relate to quality, lead time, costs, safety, and ergonomics of the product and production process. VMI standardly uses the internal CTQs of the lead time, costs, and safety as the key performance indicators (KPIs) to measure the performance of all production processes. The quality-related internal CTQs are product-specific, and VMI has defined three KPIs for the lever. As mentioned, given the importance of ergonomics, it is an addition to this research. The performance measures that currently are in place are the internal CTQs of the CTQ tree.

3.1.2 Measurement method and frequency

To measure the current performance of the lever production process, we need a measurement method for every KPI. Therefore, we extend the CTQ tree and add for every KPI a suitable measurement method. In addition, for every measurement method, we determine the measurement frequency. Figure E.2 in Appendix E shows the extended CTQ tree. As before, we mention per CTQ the measurement method and corresponding frequency. Note that parts of the CTQ tree summarise the data collection plan at the end of this section.

Quality

Surface appearance and smoothly operating divide the quality CTQ. The surface appearance means that the components should not have any surface defects. Visual inspection of the lever and its components can detect any defects on the surface. Currently, the employees perform the inspection during the assembly of every lever. Therefore, we use check sheets to record any rejected components. They allow the employees to log these rejected components per cause easily.

Smoothly operating mentions the alignment of parts and assembled according to instructions. Using a go or no-go gauge, the employees check the alignment of bush bearings in the pivot block, mentioned in 2.5.2. They execute this inspection after every glued pivot block. A lever assembled according to instructions represents the intermediate checks and final check of a lever. The intermediate checks are the points mentioned in the assembly steps two to five, discussed in Appendix F. The employees assess the same aspects of a finished lever during the final check. To record any faulty products, we use check sheets. Check sheets allow the employees to log rejected products per cause easily.

Lead time

The cycle time and waiting time split the lead time CTQ. The latter mentions the planned time minus actual product delivery and the idle time between material supply and finished levers. To determine the lateness, we can use ERP data. The ERP system logs the date when the employees give the ready signal of a PO. If we subtract the actual from the planned ready signal, a positive value equals lateness. The ERP data allows determining the lateness of every logged lever PO. The idle time between material supply and a finished lever represents the time components and subassemblies lay idle in the shelf racks. Using a video study, we can trace the components during their stay in these shelf racks. During the duration of the video study, we can trace every PO and determine the idle time.

The cycle time splits into value-adding (VA) time, necessary non-value-adding (NNVA) time, and unnecessary non-value-adding (UNVA) time. To determine the proportion of time spent on, for example, the VA activities, we use work sampling. It is a statistical technique that aims to determine the proportions of time spent on different activity categories using random observations of the subjects of interest. The desired level of statistical accuracy determines the number of observations: the sample size (Groover, 2014). Work sampling is the most appropriate measurement technique for this research. Other measurement techniques, direct time study, predetermined motion time systems, and standard data systems, are also suitable. However, there is a trade-off between the relative level of accuracy and the required analysis time. Work sampling offers relatively fair to good accuracy and requires medium time for the analysis. A predetermined motion time system is a high accuracy, time-consuming technique. In addition, a standard data system uses time standards based on historical data, for example, previous direct time studies. This technique is not convenient since we need to define these time standards for the sheltered workshop first. Finally, using a direct time study may cause discomfort to the employee due to continuous observation, unintentionally influencing the results (Groover, 2014).

Sample size

Work sampling estimates the proportions of time spent on different activities with a defined degree of statistical accuracy by using random sampling techniques to study work situations. Its statistical basis is the binomial distribution, where p is the true proportion of time spent on a particular activity category. The number of observations a work sampling study usually has is sufficient to approximate the binomial distribution by the normal distribution. To obtain a good estimate of p, sufficiently large random samples n should be taken. However, a work sampling study balances accuracy and analysis time by adopting a confidence level and acceptable absolute or relative error percentage e. Using the relative error is more precise but increases the sample size dramatically (Groover, 2014). We want to obtain precise results and thus adopt the acceptable relative error percentage. Equation 3.1 determines the sample size using a relative error percentage. The Z-score comes from the standard normal table based on the confidence level (Groover, 2014). We use a 95% confidence level and acceptable relative error of 5%, typical values in work sampling studies.

$$N = \frac{Z^2 \cdot (1-p)}{e^2 \cdot p} \tag{3.1}$$

Procedure work sampling

To determine the proportions of time spent on working activities, we perform the following steps in the work sampling study:

1. Define the activity categories.
2. Perform a preliminary sample of 100 observations to estimate p.
3. Determine the sample size using equation 3.1.
4. Schedule the random observations.
5. Observe and record the activities.
6. Determine time proportions activities.

Most of these steps are self-explanatory. However, we highlight the two steps that define the activity categories and plan the random observations.

1. Define activity categories

The activity categories are the states of the workers. They should be defined in such a way that the observer recognises them instantaneously and that they are mutually exclusive (Groover, 2014). Table 3.1 lists the activity categories we use for the work sampling study. Also, it links these categories to VA, NNVA, and UNVA time.

Table 3.1: Activity categories in the work sampling study linked to the KPIs.

Category	Description	KPI
1. Study	Worker is studying instructions or PO.	NNVA
2. Setup	Worker is preparing the workstation.	NNVA
3. Material handling	Worker is collecting or storing components.	NNVA
4. Assembly	Worker is assembling the lever.	VA
5. Quality control	Worker is checking the process quality.	NNVA
6. Clean up	Worker is cleaning up the workstation.	NNVA
7. Personal	Worker is taking personal time, (rest) break.	UNVA
8. Away	Worker is not in sight of the camera.	UNVA
9. Repair	Worker is repairing a faulty product.	UNVA

4. Schedule observations randomly

The video study for work sampling collects data for four weeks by taking a photo every ten seconds during working hours. Every snapshot yields the activities of the employees. However, we need perspective to determine accurately what the true activity is. Therefore, we study five consecutive photos, with the middle photo being the observation. To randomise the observation times, we perform an equal number of observations per production hour, scheduled by a pseudo-random number generator.

Costs

The costs are the direct assembly costs. They are the cycle time per PO. We can retrieve this data from the ERP system since the employees log the hours needed to complete a PO. The ERP data allows determining the direct assembly costs of every logged lever PO.

Safety

The safety CTQ starts with the RI&E that splits into LITFR, TRIFR, and the number of (near) incidents. The department quality, environment, safety, and health (QESH) of VMI logs these internal CTQs. Therefore, we can use the data of QESH to determine these KPIs. The department logs every occurrence of a (near) incident and determines the LITFR and TRIFR over a year. So, consulting the QESH data is the measurement frequency.

Ergonomics
The ergonomics mentions the physical workload. It translates into the ergonomics score of the production process. However, VMI currently has no suitable method to quantify ergonomics. Fortunately, many assessment tools for various aspects of physical workload are available in the literature. However, often it is not necessary to assess every aspect of physical workload. Therefore, both TNO and SDU/VHP each offer a checklist to assist in risk assessment, called checklist physical load and Fysisnel, respectively. They provide insight into possible physical risks related to the workload of a task. If an aspect of the physical workload does not lead to any risks, no further action is required. The checklists do not require any prior knowledge of risk factors or physical workload to use them (Peereboom, 2015; TNO, 2020). If there is a potential risk, we can narrow the search area for potential assessment tools. So, the next logical step is to carry out the physical load and Fysisnel checklists, the measurement frequency. The outcomes will determine the focus in the literature review if needed.

3.1.3 Priority

Prioritising the internal CTQs is the next logical step, given their number. Therefore, we extend the CTQ tree and rate the KPIs. The scores range from one to five, where five means the highest priority. We base the priority number on the preliminary findings, research scope, and VOB. The performance measurement includes only the KPIs that have a priority number of four or higher. The other KPIs are less important, given their priority number. Figure E.2 in Appendix E shows the CTQ tree. In the following paragraphs, we discuss, per CTQ, the priority numbers.

Quality
The number of surface defects refers to the component quality. VMI logs products with surface defects as an NCP. Recall that the problem context mentioned in Section 1.3 that the total number of NCPs within production group E720 is negligible. Therefore, it has a priority of one. However, the supervisor of the production group stressed the importance of process quality. Hence control is an essential aspect of the production processes. So, the priority numbers for the alignment of parts and assembled according to instructions are four and five, respectively. The first receives a lower score since it is an intermediate inspection. The other is the final inspection.

Lead time
The VA, NNVA, and UNVA times are aspects included as assembled efficiently in the VOB. Also, since production management desires to increase productivity by a capacity increase, the priority numbers for these KPIs are four. A relevant aspect of the capacity increase is reorganising the material supply. However, the primary focus is not on reducing the idle time of materials between material supply and finished lever. Hence, the priority number is one. The outline of the production process of the lever, subsection 2.5.2, indicated that the lever is an anonymously produced product. Anonymous parts are stored in high quantities and act as a buffer for fluctuations in demand. It means that the lateness of levers has less impact than with project-based parts. Therefore, the planned time minus actual product delivery has a priority number of two.

Costs
The cycle time per PO has a priority number of five since production management finds the production costs particularly important for the sheltered workshop.

Safety

The QESH department keeps an up-to-date record of the number of (near) incidents, LITFR and TRIFR. Consulting this data reveals that the number of (near) incidents related to lever production is from 2016 to 2020. The supervisor of the production group E720 endorses this finding, , as Table G.1 in Appendix G shows. Therefore, the safety-related KPIs have a priority number of three.

Ergonomics

Ergonomics is a CTQ in the CTQ tree since its importance is stressed repeatedly by people concerned with the production group. It is a relevant aspect of this research and hence has a priority of four.

The prioritisation of the KPIs leaves a selection of the KPIs for performance measurement. Figure 3.1 shows the CTQ tree of the lever that omits the redundant parts.

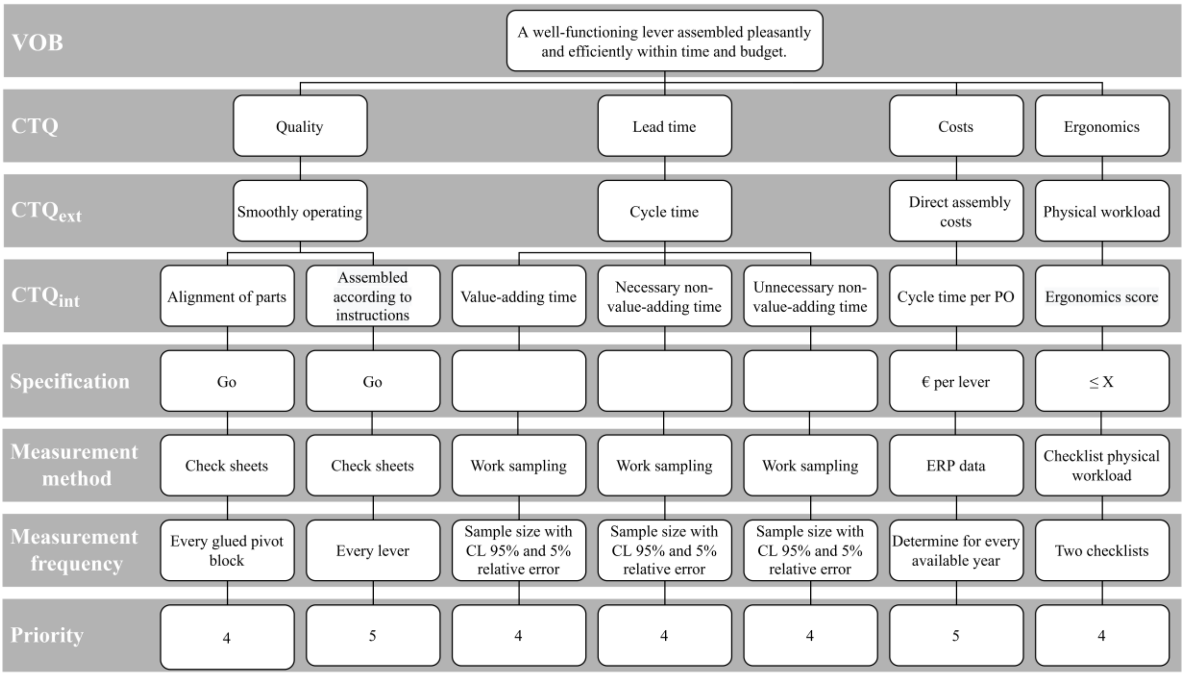

Figure 3.1: Section of the CTQ tree used as input for performance measurement.

3.2 Measurement system analysis

To verify whether the measurement systems are reliable and the data they generate are valid, we carried out measurement system analyses (MSAs). Attribute agreement analyses assessed the two measurement systems for the two quality KPIs alignment of parts and assembled according to instructions. We did not study any of the other measurement systems used for the performance measurement. An MSA of the lead time KPIs would assess photos and determine the activity category of the employee. However, perspective is needed to determine accurately what the true activity is. Otherwise, the observation could, for example, be assembly, whereas the true activity is the employee repairs a lever. Thus, an MSA of the lead time KPIs does not ensure the measurement system is reliable since the MSA itself is not valid. In addition, the ERP system logs the start and end times of a PO. The registrations do not require any interpretation, and thus an MSA is not necessary. Lastly, the ergonomic checklists based their questions on national and international standards (Visser et al., 2008). Hence, if the answer to a question reflects bad ergonomics conditions, the results of the checklists will yield a corresponding outcome. There can be no other outcome.

The two attribute agreement analyses assessed three employees on repeatability, reproducibility, and accuracy. For this purpose, the employees independently assessed 30 pivot blocks and 30 levers twice, given in Figure 3.2 and Figure 3.3. Between the assessments, we exchanged the parts as suggested by the generated run order in Minitab. As a threshold value for good agreement on, for example, repeatability, we used a kappa value of 0.75. Kappa is the ratio of the proportion of times that the appraisers agree (corrected for chance agreement) to the maximum proportion of times that the appraisers could agree (corrected for chance agreement). The kappa values range from -1 to +1, and the higher the value, the stronger the agreement (Minitab, 2019). Appendix H elaborates on the MSA and the use of attribute agreement analyses. Moreover, it discusses the approaches for the alignment of parts and assembled according to instructions. Subsection 3.2.1 and subsection 3.2.2 mention the main findings of the attribute agreement analyses of the alignment of parts and assembled according to instructions.

Figure 3.2: Pivot block arrangement for the attribute agreement analysis.

Figure 3.3: Lever arrangement for the attribute agreement analysis.

3.2.1 Alignment of parts

The attribute agreement analysis of the alignment of parts resulted in the following findings:

Confidential

The graphical output of the repeatability and accuracy of the employees, given in Figure 3.4,

Confidential

The higher the kappa value, the smaller the confidence interval. The attribute agreement analysis revealed that the employees need additional training. Also, the need for clear quality standards and the standardisation of procedure and go or no-go gauges. Finally, the analysis indicated that we should critically assess this part of the baseline performance. It may not be reliable.

Confidential

Figure 3.4: Repeatability within appraisers (l) and accuracy of each appraiser versus the standard (r).

3.2.2 Assembled according to instructions

The attribute agreement analysis of assembled according to the instructions resulted in the following findings:

Confidential

The graphical output of the attribute agreement analysis, given in Figure H.4 in Appendix H, yields similar results as the previous analysis:

Confidential

Hence, based on the second attribute agreement analysis, we concluded that the employees need additional training. Also, the analysis revealed the need for clear quality standards and the standardisation of the procedure. Finally, we should also critically evaluate this part of the baseline performance. It also may not be as reliable.

3.3 Baseline performance

The baseline performance discusses the current performance of the lever assembly process per CTQ. First, subsection 3.3.1 mentions the quality aspects of the performance. Subsection 3.3.2 presents the performance of the lead time KPIs. Afterwards, subsection 3.3.3 gives the cost-related performance of the lever. Then, subsection 3.3.4 describes the preliminary findings of the ergonomic study on the assembly process of the lever. Subsection 3.3.5 finalises this section by discussing the validity of baseline performance.

3.3.1 Quality

The employees recorded quality-related issues on check sheets per assembly step between June 7 and June 25, 2021. In these three weeks, they noted problems on levers assembled. It is important to note that these results need validation, given that the outcomes of the MSAs discussed in subsection 3.2.1 and subsection 3.2.2. The number of quality issues may not be reliable. The validation of these results and the other baseline performance results are in subsection 3.3.5. For the sake of completeness, we discuss the results of quality. Figure 3.5 gives the number of issues per assembly step over the days. It reveals that the employees encountered of the problems in the assembly step where the lever base joined the pivot block. All of the reported issues resulted in a repair, and none were unrepairable. Hence, the rework only used time and some replacement components.

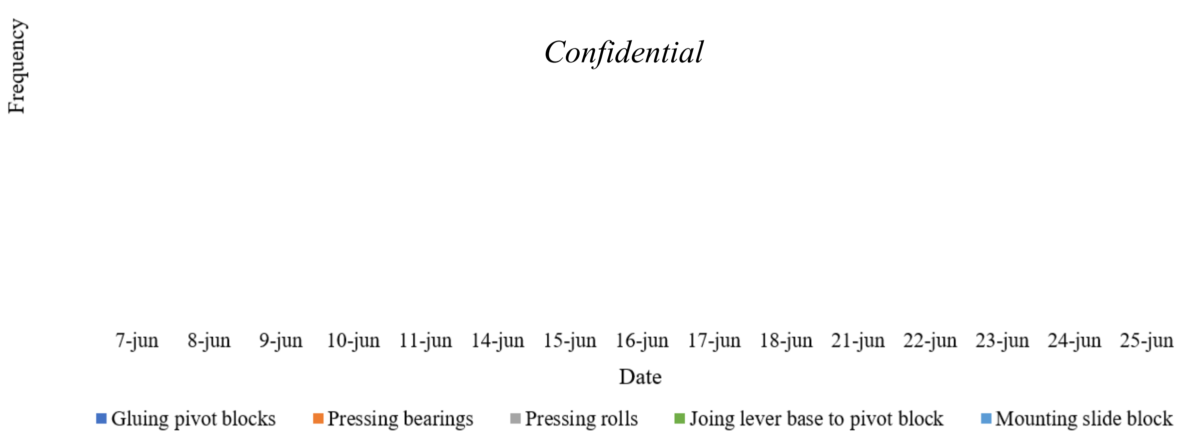

Figure 3.5: Number of quality issues per assembly step over the days.

3.3.2 Lead time

The preliminary sample of 100 observations resulted in the lever assembly having a % UNVA time. To state this with a 95% confidence level and 5% acceptable relative error, we needed to conduct observations. The preliminary samples of the assembly steps gave one assembly step with a % NNVA time. It was the lowest percentage for which we had to determine the sample size. Hence, with a 95% confidence level and 5% acceptable relative error, we needed to carry out at least observations. However, we decided to let every assembly step have an equal share in the cycle time distribution. So, we conducted just over 6150 observations per assembly step. It is an analysis of 85 production hours between June 7 to July 2, 2021.

During lever assembly, the employees spent % of the time on VA activities, as Table 3.2 lists. Simultaneously, the NNVA and UNVA activities both have a share of %. It means that the employees spent % less time on VA activities during the assembly of levers than specified. In addition, it contributes to the % and % excesses on the NNVA and UNVA time, respectively. Table 3.2 also lists the VA, NNVA, and UNVA percentages of every assembly step. It reveals that the fourth assembly step has the lowest percentage of VA time. The quality issues mentioned in subsection 3.3.1 may be a potential cause of this percentage. It is the assembly step where the employees noted the most quality issues. Also, Table 3.2 shows that the pressing of the rolls has the lowest percentage of NNVA time of all assembly steps. Finally, the glueing of the pivot blocks has the highest percentage of VA time and the lowest percentage of UNVA time.

Table 3.2: Cycle time distribution of the lever assembly and per assembly step.

	VA	NNVA	UNVA
Lever assembly overall	%	%	%
Assembly step:			
1. Glueing pivot blocks	%	%	%
2. Pressing bearings	%	%	%
3. Pressing rolls	%	%	%
4. Joining lever base to the pivot block	%	%	%
5. Mounting slide block	%	%	%

3.3.3 Costs

VMI has defined time standards for assembling the various types of levers. These time standards, combined with the costs per hour that VMI incurs to employ someone in the sheltered workshop, are the costs for assembling a lever. These assembly costs are € for the standard levers and € for the clip bar levers. Figure 3.6 shows the average assembly costs relative to the calculated assembly costs per type of lever per year. It indicates that the employees are generally . Between 2016 and 2020, the actual average assembly costs for a standard lever were € , which is % than calculated. The mechanical and vacuum clip bar lever had average assembly costs of € and € . These are % and % than expected. However, the employees assembled the standard than expected in 2018. It is only time that the employees assemble a type of lever budget.

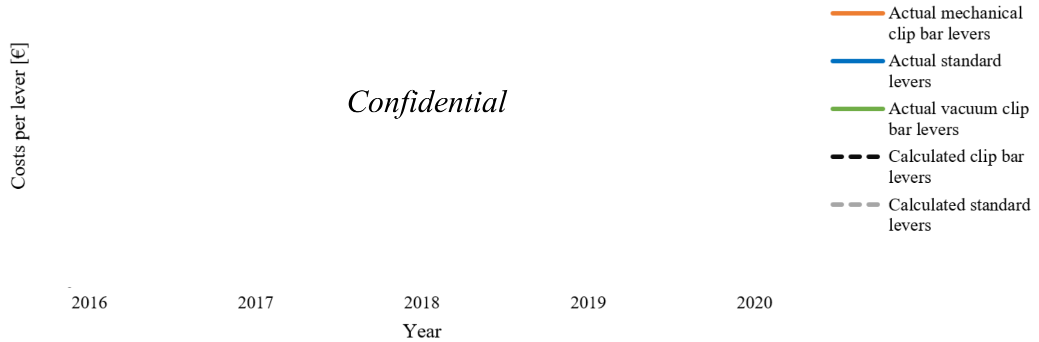

Figure 3.6: Calculated and actual costs per standard lever, mechanical, and vacuum clip bar lever over the years.

3.3.4 Ergonomics

The TNO and Fysisnel checklists are comprehensive questionnaires on aspects such as carrying, lifting, repetitive motions, and working postures. As mentioned, these checklists do not require any prior knowledge of risk factors or physical workload to use them. Hence, a multidisciplinary team first filled in the questionnaires separately. The instructions were to base the answers on normal working conditions. After discussing the differences, we determined that misinterpretation and incorrectly answered questions caused the differences.

The Fysisnel checklist uses risk assessment scores per aspect ranging from one, abominable, to ten, excellent. It scores the lever assembly on all aspects an eight or higher, as Table 3.3 depicts. In that case, the checklist states that there is no need to undertake action. The TNO checklist uses a three-colour traffic light to score the risk assessment per aspect. It gives the lever assembly on all aspects a green score, summarised in Table 3.4. Therefore, the TNO checklist states that there is no need to perform a detailed assessment or fill out another assessment form. So, we do not need to study the literature to determine suitable quantifying ergonomic tools.

Table 3.3: Risk assessment scores of the lever assembly per aspect using Fysisnel.

Activity	Lifting	Carrying	Pushing & pulling	Vibrations	Working postures	Repetitive motions	Energetic load
Scores risk assessment	9	10	8	10	8	8	10

Table 3.4: Risk assessment scores of the lever assembly per aspect using the TNO checklist.

Activity	Risk assessment score	Activity	Risk assessment score
Lifting and carrying	Green	Hand-arm vibration	Green
Pushing and pulling	Green	Whole body vibration	Green
Hand-arm tasks	Green	Energetic overload	Green
Working postures	Green	Energetic underload	Green
Computer-related work	Green	Existence of task-related complaints	Green

To summarise the baseline performance, we return the values to the CTQ tree. Figure 3.7 presents the current performance of the lever production process. Next, we discuss the validity of the baseline performance.

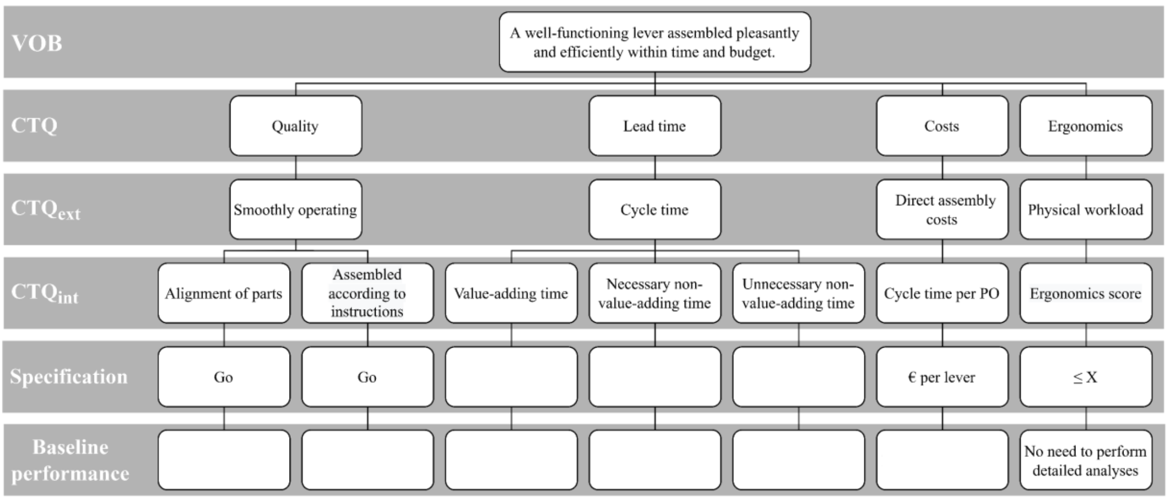

Figure 3.7: Overview of current performance lever production process.

3.3.5 Validity

The MSAs revealed that the quality-related data may not be reliable. Hence, we question these results and the other aspects of the baseline performance. The baseline performance has to represent reality well enough to be able to compare it with the future state performance.

Quality

The employees reported quality issues on levers assembled. However, we excluded problems since we could trace them to an NCP. Hence, the true number of quality issues was on levers assembled. The NCP was a batch of components causing issues when the employees joined the lever base to the pivot block. Rework resolved the issue on June 10. We excluded these issues since the number of NCPs that state components of the lever are not according to specifications is small, as Table A.2 in Appendix A lists. The number of NCPs was and in 2019 and 2020, respectively. It shows that the impact of an NCP on the lever production process can be high, although the number of NCPs is relatively low. A rejected batch size of components is generally a high quantity.

The results of the attribute agreement analyses stressed assessing the data critically. The employees did not always agree with the known standard in these analyses. The reported quality issues were the number of repairs performed. It means the lever could not function without rework. Hence, we can rule out the lever was a go part assessed as a no-go. Note that half of the disagreements with the known standard in the attribute agreement analysis were parts assessed as no-go while these parts were conforming parts, listed in Table H.3 and Table H.8 in Appendix H. The latter table shows that it is also likely that non-conforming levers did pass inspection. It means that the number of quality issues could be higher. Thus, based on the attribute agreement analyses, the number of quality issues is likely higher than the reported.

The video study revealed that only one employee noted the encountered quality issues. This employee assembles levers practically every day. In those three weeks, the employee assembled levers of the levers. Hence, it is likely that there were more quality issues, but only not noted. The video study data indeed reveals that other employees encountered quality issues. Determining how many issues there were is too time-consuming. It requires analysing the entire video study when other employees were assembling levers.

The previous points indicate that the collected data of quality is not completely valid and reliable. Likely, the number of quality issues is higher and certainly not lower due to the accuracy of the employees and unreported quality issues.

Lead time

The abovementioned NCP disturbed the process to such an extent that we decided to exclude the data from June 7 to June 10 from the work sampling study. It could bias the VA percentage, for example. Especially since only a small number of NCPs state that the lever components are not according to specifications. Therefore, we divided the scheduled observations for those four days equally over the remaining production hours.

The work sampling study consisted of over 30 thousand observations and used the acceptable relative error to obtain more precise results. The confidence level and the number of observations allow to determine the absolute error. Hence, with a 95% confidence level, the lever assembly process consists of % ±0.6% VA time, % ±0.5% NNVA time, and % ±0.5% UNVA time. The large number of observations spread over four weeks and excluding highly disturbed data ensures representative results.

Costs

The logged production hours per PO determined the assembly costs per lever. It revealed the employees generally . However, the data is non-normally distributed. The data of the standard levers, for example, has a mean of minutes with a standard deviation of minutes. The data has a high number of outliers. It has a skewness of 7 and a kurtosis of 90, as Figure 3.8 shows. After removing a large number of the outliers, we still could not fit any distribution to the dataset. We used a goodness-of-fit test with the individual distribution identification function within Minitab. None of the 14 possible probability distributions had a p-value greater than 0.05. Figure I.1 in Appendix I lists the results of fitting the probability distributions to the dataset. Figure I.2 in Appendix I visualises the results of fitting the exponential, gamma, lognormal and Weibull distributions to the dataset. Overall, it is highly likely that employees did not always correctly log their assembly hours. The data of the video study, for example, shows that an employee is glueing pivot blocks, whereas the employee did not log these assembly hours. Also, during logged production hours, employees assembled other products. So, the collected data on costs is not completely valid and reliable.

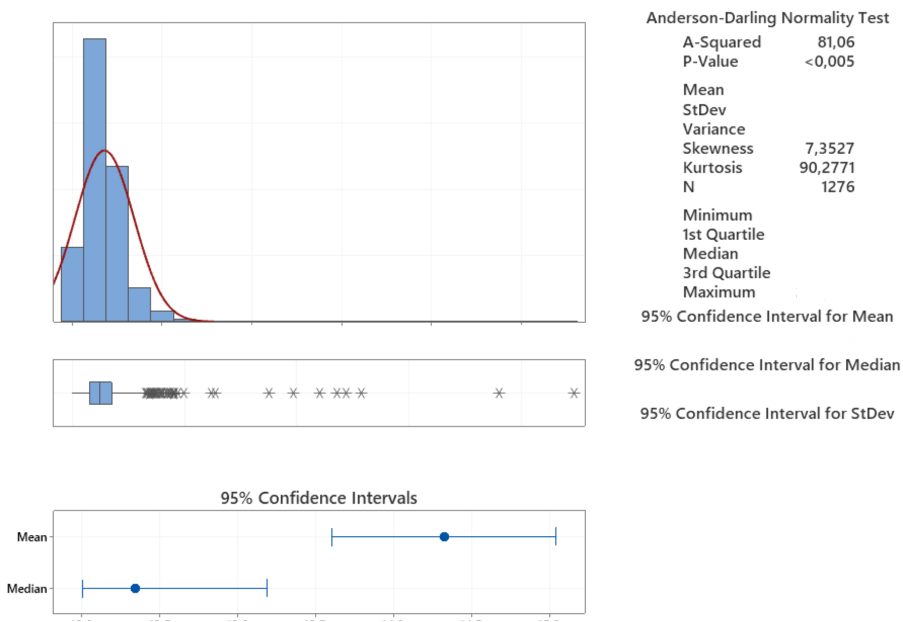

Figure 3.8: Descriptive statistics of the dataset cycle time per standard lever.

Ergonomics

The use of two different checklists ensured reliable, ergonomic risk assessment. They determined risk assessment scores using different questions for similar aspects (e.g., pushing and pulling). The checklists indicated there is no need to perform detailed analyses of the lever assembly. Moreover, the fact that the risk assessment scores of Fysisnel are high means that the ergonomic conditions should be good. However, it does not explain why some employees experience health complaints. Since the activities themselves are not the cause, the way the employees perform the activity is likely the cause. Someone in the multidisciplinary team underlined it . The results may be reliable, but they do not take into account individual ways of working. Thus, it does not represent reality well enough. So, determining whether the health complaints originate from an incorrect way of working is the next step of the ergonomic study.

3.4 Conclusion

The third chapter focused on determining the current performance of the lever production process. First, we created a data collection plan. Then, we assessed the validity of two measurement systems. Finally, we presented the baseline performance and its validity. Thereby, the chapter answered the second research question: "*What is the current performance of the selected production process at production group E720?*".

Currently, there are 13 performance measures in place for the lever production process. They relate to quality, lead time, costs, safety, and ergonomics. Prioritisation of these KPIs left seven KPIs. Quality has the alignment of parts and assembled according to instructions. Lead time has VA, NNVA, and UNVA time. Costs and ergonomics have cycle time per PO and ergonomics score, respectively. The additions of the measurement method and frequency completed the data collection plan, summarised in Figure 3.1.

The attribute agreement analyses assessed the measurement systems used for the two quality KPIs alignment of parts and assembled according to instructions. They found the repeatability

. Therefore, the employees need training, clear quality standards, and standard procedures and measurement instruments.

The baseline performance revealed quality issues on levers assembled. However, this number is not completely representative and reliable. It is likely higher. The attribute agreement analyses revealed that employees let non-conforming levers pass inspection. Furthermore, only one of the four employees levers reported quality issues. In addition, we excluded quality issues due to an NCP to improve the representativeness. It revealed that the impact of an NCP in the lever assembly process can be high, although the number of NCPs is relatively low.

The cycle time of the lever assembly consists of % VA time, % than specified. Simultaneously, the NNVA and UNVA time are both %, which are % and % than specified, respectively. The large number of observations spread over four weeks and excluded disrupted data ensured representative values.

The pre-calculated assembly costs for a standard lever are € and € for a clip bar lever. However, the actual average costs for a standard lever, a mechanical and vacuum clip bar lever were € , € and € , respectively. Nonetheless, the production hours are likely not always correctly logged. The data has a high number of unrealistic outliers.

The ergonomics study used two ergonomic checklists to narrow the scope of potential assessment tools. These checklists evaluate different aspects of the workload without requiring any prior knowledge. Both checklists concluded that there is no need to perform detailed analyses since the ergonomic conditions should be good. However, the way the employees perform the activities likely causes health complaints, not the activities themselves.
. The results are reliable but not viable since they do not take into account individual ways of working. Determining if the health complaints originate from an incorrect way of working is the next step of the ergonomic study.

The third chapter determined the current performance of the lever production process does not meet the specified requirements in terms of the CTQs . Therefore, Chapter 4 analyses the current performance to identify factors that cause the lever production process not to meet these requirements.

4 Performance analysis

The fourth chapter analyses the current performance of the lever assembly process since the production process does not meet the specified requirements in terms of . First, Section 4.1 lists and selects analysis tools for the performance analysis. Section 4.2 analyses the current process. Then, Section 4.3 identifies and selects influence factors that affect the performance of the lever assembly. Section 4.4 finalises the chapter by concluding the main findings.

4.1 Analysis tools

To analyse the current performance, we use a selection of tools. It is key that these tools align with the current issues. The problem context, Section 1.3, and baseline performance, Section 3.3, outlined several problems. At a top level, we group these issues under facility layout, material supply, and process performance. In Lean Six Sigma DMAIC projects, a tool frequently used to analyse facility layout is a spaghetti diagram. Swimlanes, process flow diagrams, and a value stream map (VSM) help understand processes better, such as the material supply, assembly process, and other related processes. Lean Six Sigma DMAIC projects can use brainstorming sessions, a cause and effect diagram, and five times why to analyse process performance and identify root causes. Afterwards, these projects generally use a decision matrix or a cause and effect matrix to select the main influence factors for the improvement phase.

We use spaghetti diagrams to determine the efficiency of the facility layout. To analyse the material supply, we select swimlanes over process flow diagrams. Swimlanes also identify the people responsible for the process tasks. In addition, we can use swimlanes to obtain a better understanding of other (sub)processes of the lever assembly. Also, we use a VSM. It is a high-level visualisation of the lever assembly process. To identify the root causes of the process performance, we select the cause and effect diagram. It uses a brainstorming session to list potential causes and serves as an effective means to apply five times why. Finally, we use a cause and effect matrix to select influence factors. It takes into account the VOB when scoring the factors.

4.2 Process analysis

The process analysis starts with analysing the facility layout using spaghetti diagrams in subsection 4.2.1. Afterwards, subsection 4.2.2 details subprocesses of the lever assembly through swimlanes. Subsection 4.2.3 visualises the lever assembly with a VSM.

4.2.1 Spaghetti diagrams

Spaghetti diagrams determine the efficiency of the facility layout. They visualise the movements of a person, product, or document. A spaghetti diagram helps identify motions where time and energy are wasted (Theisens, 2017). As the assembly of the levers is a batch process, discussed in subsection 2.5.4, we draw a spaghetti diagram for each of the five assembly steps to keep them understandable. Every spaghetti diagram represents the movement of an employee during the assembly of a batch of 45 levers. We followed the motions of the employee by using the photos collected for the work sampling study. We only highlight the spaghetti diagram of the fourth assembly step, joining the lever base to the pivot block, given in Figure 4.1. It had the lowest VA percentage and more of the quality issues of all assembly steps, mentioned in the baseline performance Section 3.3. Moreover, all the spaghetti diagrams show similar motion patterns as Figure J.1 to Figure J.5 in Appendix J show.

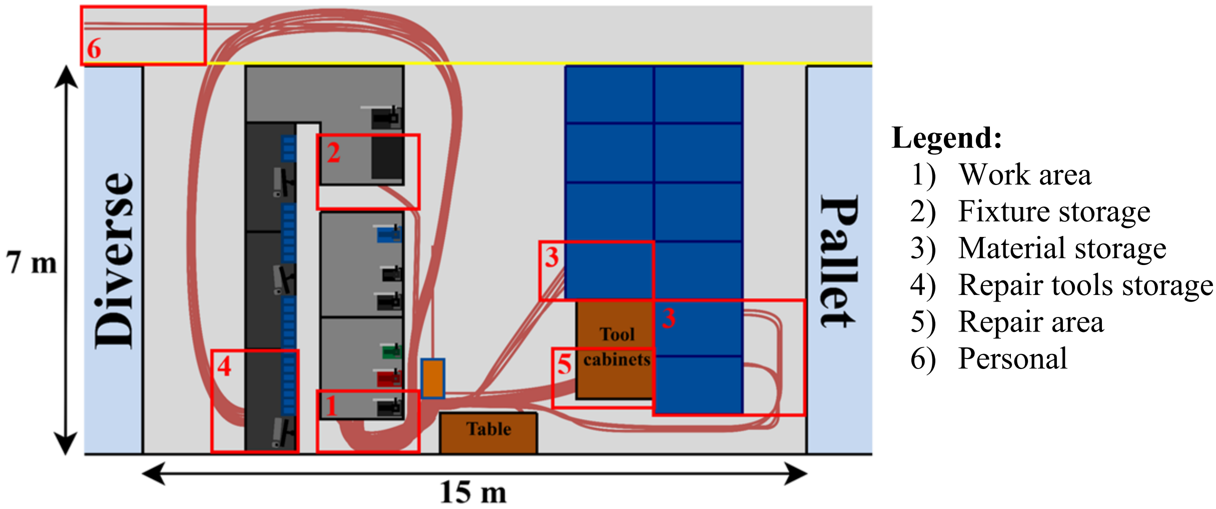

Figure 4.1: Spaghetti diagram of joining the lever base to the pivot block.

In the spaghetti diagram of the fourth assembly step, Figure 4.1, we framed and numbered seven areas in the facility layout. These numbers represent different motion activities. Joining of the lever base to the pivot block took place in area 1. To do so, the employees collected a fixture and tools from area 2. Afterwards, they gathered the components needed for the assembly step from the areas numbered 3. To repair a faulty lever, the employees collected repair tools from area 4 and performed these repairs in area 5. In between the assembly, they fetched a cup of coffee, illustrated in area 6. After finishing the batch, the employees stored the fixture, components, tools, and repair tools in their original location. The result is a repetitive cycle of movements. These repeating cycles are also visible when the employee collects and stores the fixture, materials, and tools for the other assembly steps. It helps explain why the VA percentage of the process is only %. However, it does not explain why the employees have to walk so much. Fortunately, swimlanes can provide a detailed analysis of the process. In short, the spaghetti diagrams visualise that the employees waste time on repetitive cycles of collection and storage. They help explain the % VA percentage but do not explain the reasons for so much walking. Hence, we apply swimlanes to detail the process.

4.2.2 Swimlanes

A swimlane diagram is a flow chart of a process. It consists of horizontal lanes for every actor in the process. Moreover, a swimlane lists the responsibilities of an actor in the corresponding lane. It visualises a process and helps identify improvement potential (CSSC, 2018). Based on the findings of the baseline performance and the spaghetti diagrams, the swimlanes of interest are the material supply, lever repairs, PO prioritisation, and every assembly step. We need a better understanding of why the employees are performing the tasks in the current way. In this subsection, we only elaborate on the swimlane of the material supply and the main findings of the other swimlanes. The swimlanes of the lever repairs, PO prioritisation, and every assembly step are given in Figure K.1 to Figure K.7 in Appendix K, respectively.

The swimlane of the material supply, given in Figure 4.2, shows that two processes control the inventory in the shelf racks. The MPS generates pick orders for the warehouse based on the virtual stock. In addition, the supervisor of the production group uses a manual count and the upcoming POs to order additional components if necessary. The swimlane reveals that a discrepancy exists between the ERP and physical inventory. The most likely explanation is the organisation around the repair of levers. The swimlane of the repair of levers, depicted in Figure

K.1 in Appendix K, reveals that the employee does not report any components used to rework the lever. The number of repairs performed, discussed in subsection 3.3.1, combined with no feedback on the use of additional components, causes a discrepancy between the ERP and physical inventory.

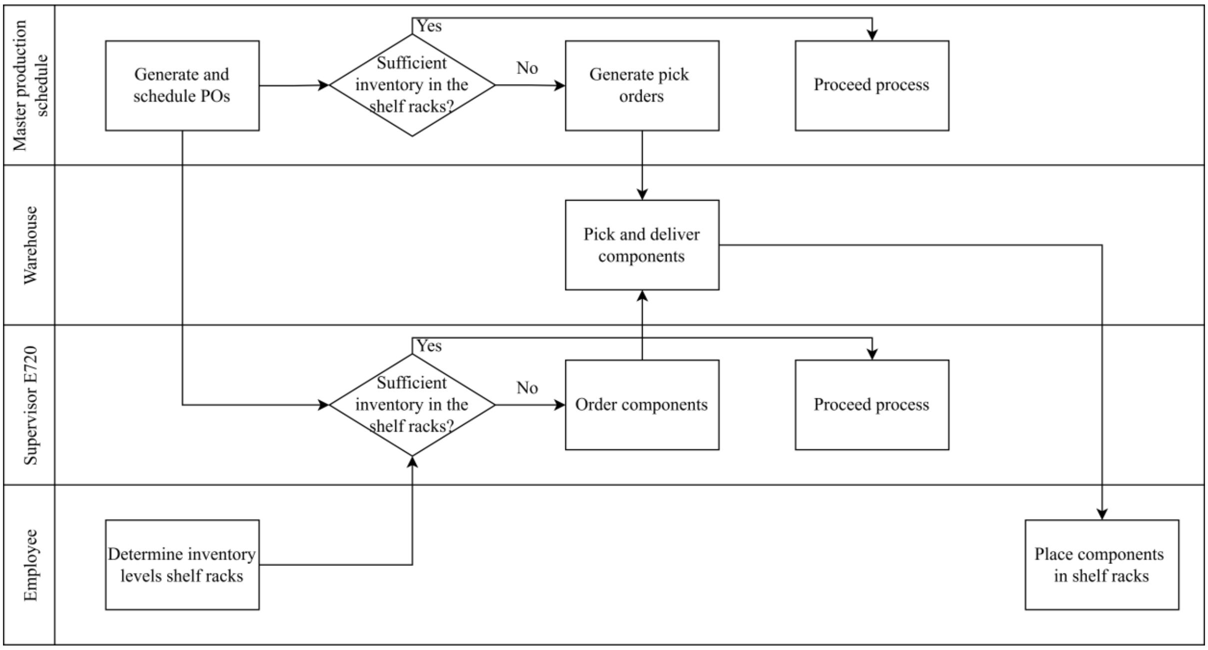

Figure 4.2: Swimlane of the material supply of the lever assembly.

The swimlane representing the repair of a lever, Figure K.1 in Appendix K, reveals that the employees consult with each other when they question the quality of the process. Whether a product passes or needs rework corresponds to the findings of the MSA, Section 3.2: the employees . In addition, the swimlane shows that not every employee has the same skillset. Hence, some employees cannot perform all rework and have to someone else. Finally, it reveals that the employees repair levers immediately after a defect occurs.

The swimlanes of every assembly step, Figure K.3 to Figure K.7 in Appendix K, show the similar repetitive cycles of collecting and storing fixtures, tools, and components as the spaghetti diagrams do. In addition, they reveal that the employees constantly have to align the lever with the tooling manually. The fixtures do not support them during assembly. For example, employees use one fixture for twelve different levers (component). These levers vary in dimensions, and hence the fixture does not constraint the levers in any way. Furthermore, they demonstrate a lot of material handling in every assembly step. The employees pick and place WIP levers from or onto trolleys.

The swimlane that visualises the PO prioritisation shows that the non-project-based POs have a lower priority, as discussed in subsection 2.5.2. Furthermore, it reveals that the employees divide the POs in the weekly schedule in consultation with each other. Lastly, the swimlane demonstrates that the employees perform quite some organisational work before PO hour registration starts.

4.2.3 Value stream map

The VSM of the lever assembly process visualises the current state. It represents the product flow from the supplier to the customer. A VSM maps each process step and lists its cycle, lead, and processing time. Furthermore, it quantifies the WIP and maps the flows of information and materials (Pyzdek & Keller, 2003). The current state VSM of the lever assembly defines the suppliers and customers based on the research scope, Section 1.4. Hence, the warehouse is the supplier, and the drum workshop and the warehouse are the customers.

The lever assembly consists of two parallel processes, as Figure 4.3 shows. The first one produces glued pivot blocks, used in the second process: the lever assembly. In the first process, we added ultrasonic cleaning. A process step not mentioned before but essential for glueing the pivot blocks. The current state VSM also shows the two inventory control policies and the absence of feedback on the use of additional components for repairs, discussed in the swimlanes.

The performance of every process step originates from the baseline performance, where we converted the number of repairs into the first time right (FTR) percentage. The cycle time per process step is the average cycle time determined over 30 batches of 45 levers. The timestamp of the work sampling photos provided the start and end times for this purpose. Overall, the assembly process of the lever has a cycle of   minutes and a   % FTR score.

The lever lead time of over   days also stands out. The high inventory levels cause components to spend an average of   days in the shelf racks before use. A manual count determined the idle time of the components in the shelf racks to be   days. In addition, only one shipment per week to the customers contributes to another   days of lead time. Also, the glued pivot blocks add   days to lead time. The curing time of the adhesive requires multiple pivot block varieties in inventory. For this purpose, the supervisor of the production group visually checks the inventory levels daily and adapts the schedule to it. The standard inventory of glued and unglued explains why the WIP time is also over   days. They act as buffers to secure the continuation of the lever assembly. Thus, next to the MPS, another production schedule exists.

The high lead time of levers results in a VA score of   %. It means that only   % of the time between component arrival and the shipment of finished levers, employees add value to the lever.

The current state VSM of the lever assembly consists of two parallel processes: glueing pivot blocks and lever assembly. The first process has its own production schedule next to the MPS. It is based on daily visual inventory checks. The cycle time of the lever assembly is   minutes, and the process has a   % FTR score. The high component inventory levels, curing time of the adhesive, and one shipment per week of finished levers results in a lead time of over   days and a WIP time of   days. Finally, the high lead time of levers results in a VA score of   %.

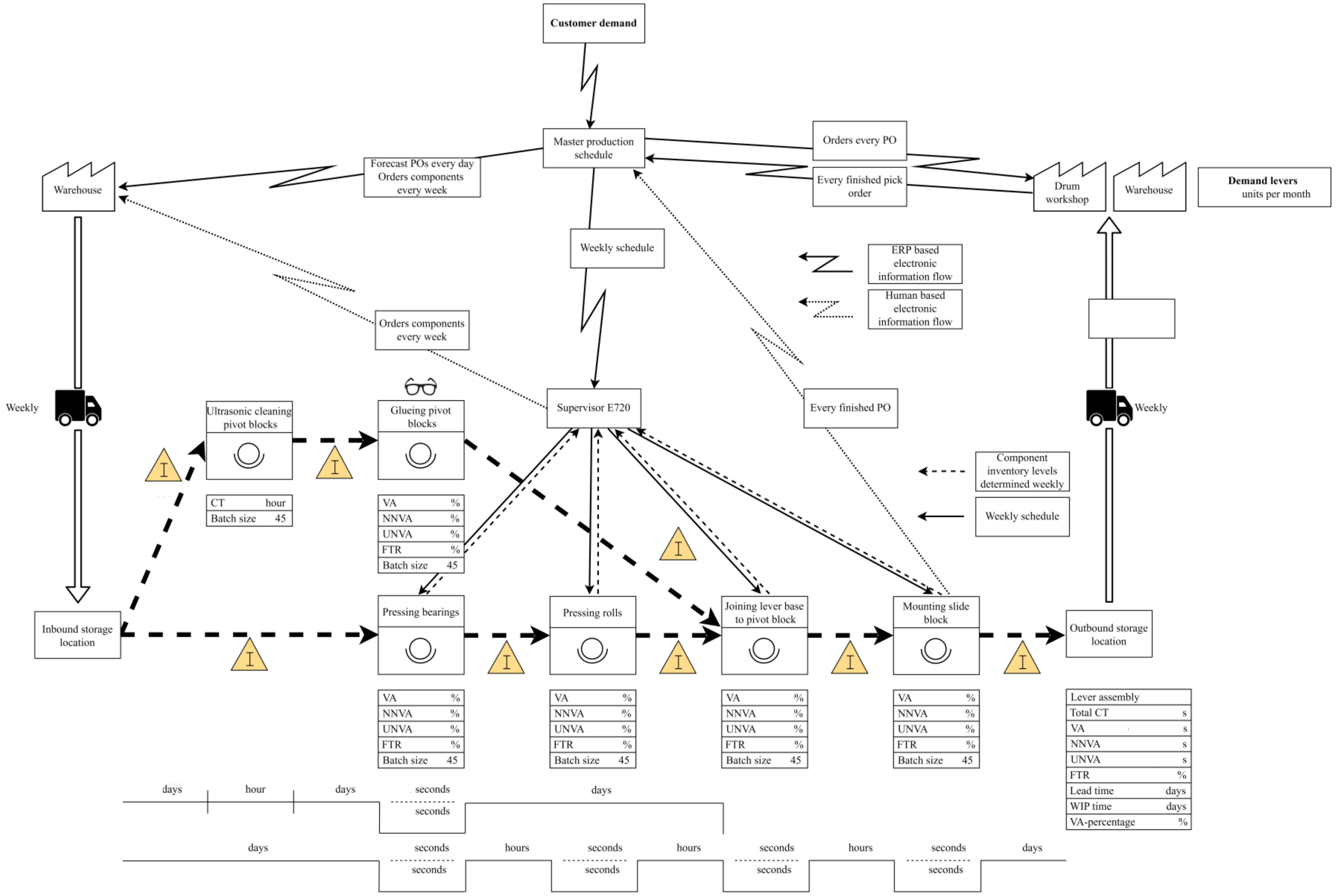

Figure 4.3: Current state VSM of the lever assembly.

4.3 Influence factors identification and selection

The previous section mentioned the first factors that influence the current performance of the lever assembly process. Hence, it is likely that more influence factors exist. Therefore, subsection 4.3.1 starts with a brainstorming session to identify potential influence factors. Afterwards, subsection 4.3.2 evaluates these influence factors using a cause and effect matrix. Subsection 4.3.3 visualises the relationships among the factors and identifies the causing factors and affected factors in an interrelationship diagram. Lastly, subsection 4.3.4 selects some causing factors and lists the improvement focus in the upcoming chapters.

4.3.1 Cause and effect diagram

To identify potential causes of the current performance, we use a fishbone diagram. A fishbone diagram is a cause and effect diagram. It is an approach where a team lists causes in a brainstorming session. Cause categories of the problem structure the brainstorming into smaller sessions (Pyzdek & Keller, 2003). In our brainstorming session, we questioned why the VA percentage only % is. After all, all causes affect the process efficiency and hence the VA and NVA percentage. The brainstorming team consisted of a multidisciplinary team. We used the standard cause categories: machines, methods, materials, manpower, measurement, and environment, where every category has its unique colour. Figure 4.4 lists per category the causes why the VA percentage only % is. It is a simplified version. Figure L.1 in Appendix L is the extended version where the fishbone diagram also lists the subcauses. Over the 26 causes, we identified an additional 66 subcauses.

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Figure 4.4: Fishbone diagram of causes influencing the VA percentage (simplified version).

4.3.2 Cause and effect matrix

The cause and effect matrix listed 26 causes that affect the current performance of the lever assembly. To prioritise the influence factors, we use a cause and effect matrix. It correlates the process inputs (X's) to the process outputs (Y's). Process owners usually determine the correlation score of each combination according to a four-point scale. In addition, it takes into account the VOB by rating the importance of the process outputs (Theisens, 2017).

In the cause and effect matrix, we place the collected influence factors in the rows and group them by their cause categories. These are the 26 causes, called the key process input variables. We place the seven selected internal CTQs, determined in 3.1.3, in the columns. These are the KPIs used to determine the baseline performance and are called the key process output variables. To rate the importance of the process outputs to the business, we use the prioritisation scores of the CTQ tree, listed in Figure 3.1. Finally, to improve the reliability of the correlation scores, a multidisciplinary team first determined the scores separately. Afterwards, we discussed the differences and agreed on the correlation scores. Table M.1 in Appendix M gives the cause and effect matrix after discussing the correlation scores.

The Pareto chart in Figure 4.5 visualises the results of the cause and effect matrix. It ranks the values of the influence factors in descending order. Hence, the three largest influence factors are . However, the first two factors are out of scope. The , which determine whether a lever , are part of the product design. Recall that the research scope in Section 1.4 excluded the product design and component quality. Nevertheless, it is interesting to note that the is a factor that has such a great influence on the performance of the process. . The two out-of-scope factors have a semi-transport colour in the Pareto chart. Therefore, the colours represent the different cause categories of the fishbone diagram, Figure 4.4. Based on this colour scheme, we can identify that the categories machines, materials, and methods consist of the factors that have the greatest influence on the performance of the lever assembly process.

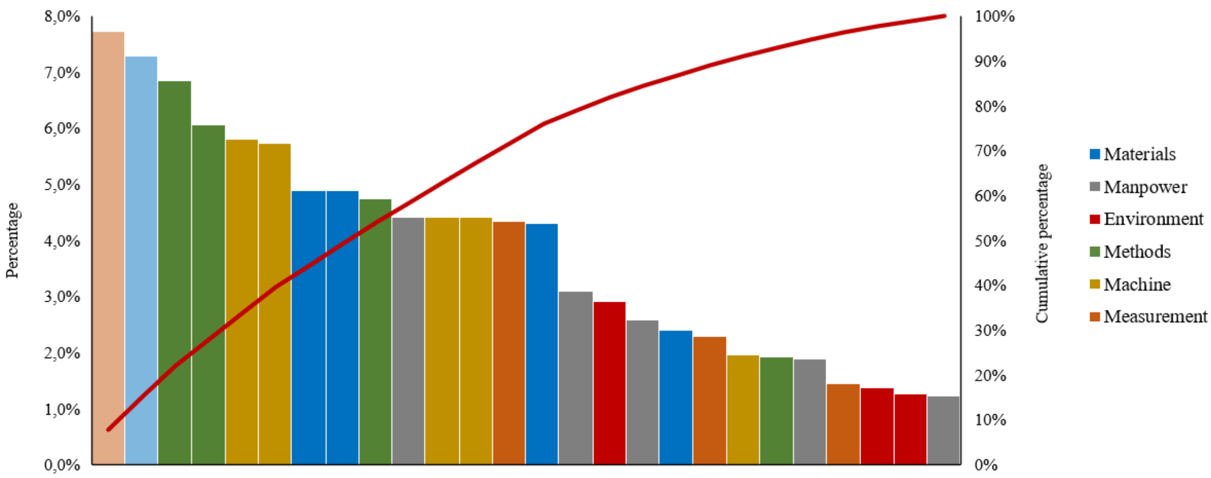

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Figure 4.5: Pareto chart of the cause and effect matrix, where the cause categories are distinguished by colour.

Usually, the cause and effect matrix combined with the Pareto chart are the tools to select a number of influence factors. However, a closer examination of the various factors reveals a strong interrelationship between these factors. For example,

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So, we have to better understand the relations between the influence factors before selecting influence factors. An interrelationship diagram is a solution for this situation and is the next research step.

4.3.3 Interrelationship diagram

An interrelationship diagram depicts the relationships among factors in a complex problem situation. It visualises and helps identify which issues are causing problems, the drivers, and which issues result from others, the outcomes. The drivers have more arrows pointing away from them than toward them and vice versa for the outcomes (Andersen & Fagerhaug, 2006).

We slightly adapt the interrelationship diagram by basing the weight of the arrows on the results of the cause and effect matrix in Table M.1 of Appendix M. It is a linear scale, where the influence factor with the higher score has weightier arrows pointing away. We use a five-point scale as the difference between the highest and lowest score is a factor of about five. In addition, it distributes the 26 influence factors evenly over the five scales. The interrelationship diagram illustrates the complexity of the problem situation, given in Figure N.1 of Appendix N. Numerous cycles between factors exist, ranging from two to over ten factors. However, some of these cycles exist of factors that relate to each other. For instance,

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as one large material inventory and control issue. So, the opportunity exists to simply interrelationship diagram. In addition, reducing the number of drivers and outcomes, which currently are 14 and 10, respectively, would also improve the understandability of the problem situation.

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Figure 4.6: Interrelationship diagram of the cause and effect matrix (simplified version).

We simplify the interrelationship diagram by merging influence factors. These factors relate to each other and are within the same cause category (i.e., are of the same colour, mentioned in subsection 4.3.2). As an example, Figure N.1 in Appendix N lists multiple and . We merge their scores and arrow weights into the factor , as

Figure 4.6 shows. The simplified interrelationship diagram lists ten drivers and eight outcomes, also given in Table 4.1. In it, the main driver is . It affects ten other factors. Of the nine other drivers, two are out of scope. These are the and discussed in subsection 4.3.2. Also, another driver characterises the process activities as accurate and precise. It is a given process characteristic that we cannot influence or change. The main outcomes are many . These aspects were also the main results emerging from the baseline performance, Section 3.3. Next, we select some of the drivers for process improvement and determine their impact in the Pareto chart.

Table 4.1: Drivers and outcomes of the interrelationship diagram.

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4.3.4 Influence factor selection

The drivers in an interrelationship diagram are usually the influence factor to choose for process improvement. The simplified interrelationship diagram, given in Figure 4.6, lists ten drivers. Recall that two of these drivers are out of scope, and one is a non-influenceable process characteristic. We select the seven remaining drivers for the new production process design. When we return them to the Pareto chart, their cumulative share is almost 57%. In addition, their impact on the outcomes has a cumulative share of about 20% in the Pareto. The remaining 23% consists of 19% of the out-of-scope factors and the process characteristic. The last 4% are three factors that are part of the bottom four factors in the Pareto chart. In other words, by tackling the seven drivers, we solve 57% of the issues. Moreover, solving these drivers could result in an additional reduction in outcomes of at most 20%. The consequences disappear when we address the causes. So, by solving seven influence factors, we can potentially solve up to 77% of the issues. To name these seven and their impact on others, we highlight them in additional Pareto, given in Figure 4.7. Thus, the improvement focus is on:

- Facility layout
- Material supply
- Process and workstation design
- Work method

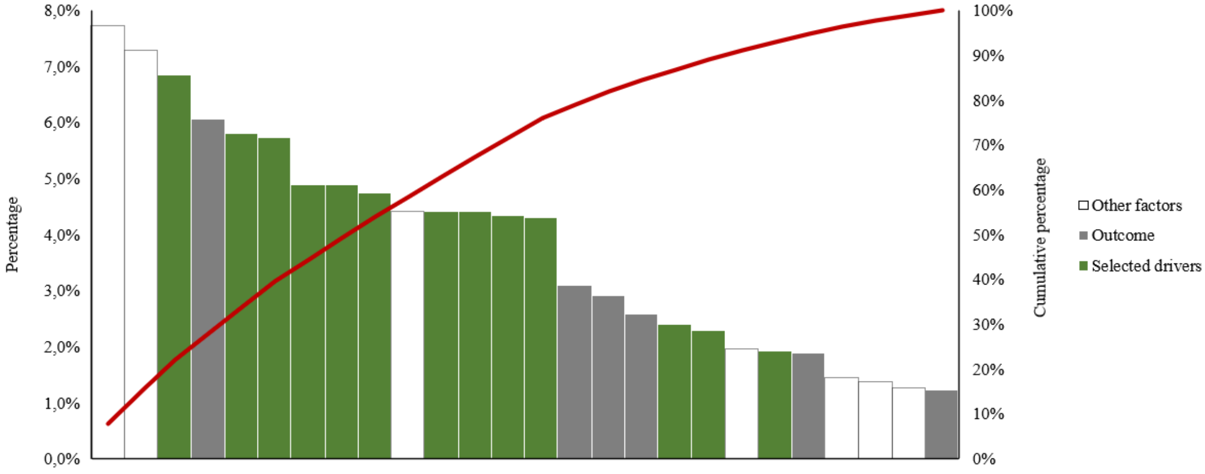

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Figure 4.7: Pareto chart with the selected drivers, outcomes, and other.

4.4 Conclusion

The fourth chapter focused on analysing the current performance of the lever production process. First, we listed and selected analysis tools. Then, we applied these tools to analyse the process. It resulted in the first causes of the current performance. Afterwards, using a brainstorming session, we listed more influencing factors. After scoring their impact on the current performance and depicting their relationships, among other factors, we selected a number of influence factors. Lastly, with the selected factors, we determined the main focus points for the improvement phase of the research. Thereby, the chapter answered the third research question: "*What factors influence the current performance of the selected production process at production group E720?*".

The spaghetti diagrams, used to determine the efficiency of the facility layout, visualised the repetitive cycles of collecting and storing fixtures, (repair) tools, and components. In addition, they showed a lot of material handling in the form of picking and storing WIP levers onto trolleys.

The swimlanes identified the tasks and those responsible for them for the processes of material supply, lever repairs, PO prioritisation, and every assembly step. They revealed that the ERP system and a physical process control the inventory levels in the shelf racks. The cause is a discrepancy between virtual and physical inventory, likely due to the
repairs and no feedback on using additional components during rework. The employees perform this rework immediately after a defect occurs, but not all the employees possess the skills to rework all defects. Also, the swimlanes again demonstrated the need
. The absence of them results in many dialogues between the employees. Moreover, they showed that the employees have to manually align the levers with the tooling to perform an assembly step. The fixtures have only a limited supporting function during assembly. Finally, the process of prioritising and selecting POs demands some organisational work.

The current state VSM visualised the flow of information and materials, mapped each process step, and overviewed the current performance. It showed that the lever assembly consists of two parallel processes. The first one produces glued pivot blocks, used in the second process: the lever assembly. In the first process, we added ultrasonic cleaning. A process step not mentioned before but essential for glueing the pivot blocks. The glueing of the pivot blocks has its own production schedule based on daily visual inventory checks, whereas the MPS schedules the POs for the lever assembly. The cycle time of the process is minutes, and the process has a % FTR percentage. The high component inventory levels, curing time of the adhesive, and one shipment per week of finished levers results in a lead time of days and a WIP time of days. Lastly, the high lead time of levers results in a VA score of %.

The cause and effect diagram identified 26 causes and 66 subcauses, over the categories machines, methods, materials, manpower, measurement, and environment, why the VA percentage is only %. After scoring the impact of the 26 causes, using a cause and effect matrix, we determined that the two greatest influence factors (i.e., and) are out of scope, given the research scope. Furthermore, between the various influence factors exist relationships. Thus, we composed an interrelationship diagram to depict the relationships among the influence factors. The simplified interrelationship diagram listed ten drivers and eight outcomes. We selected seven of these drivers after excluding the out-of-scope drivers and a non-influenceable process characteristic. Tackling these seven drivers solves 57% of the issues and reduces the impact of outcomes by an additional 20%. Thus, we can potentially solve up to 77% of the current issues when we develop solutions for these main influence factors. The seven selected drivers relate to facility layout, material supply, process and workstation design, and work method.

The fourth chapter determined the main improvement focus for the next chapters. It starts with a literature review in the areas that relate to, for example, the facility layout and material supply in Chapter 5. The literature review can provide knowledge and insights that may facilitate the redesign of the production process.

5 Literature review

The fifth chapter discusses literature relevant to this research and is organised as follows. Section 5.1 mentions several design frameworks. Then, Section 5.2 discusses the facility layout and relevant aspects to consider. Section 5.3 describes relevant aspects of the material supply. Next, Section 5.4 elaborates on tools to develop the workstations and design fixtures. Section 5.5 discusses available related work in the literature. Section 5.6 summarises the main findings.

5.1 Design framework

A manufacturing system includes all activities and elements needed to transform a set of inputs into products and services. It consists of a number of subsystems with relationships between them and their environment. Groover (2015) defines the following four subsystems of a production system:

- Processing and assembly. The machines, tools, fixtures, and other related hardware of the production system.
- Material handling and storage. The hardware for moving and storing materials between processing and/or assembly operations.
- Human workers. The required direct and indirect labour to operate and manage the production system.
- Coordination and control. The regulation of individual processing and assembly operations and the management of plant-level activities.

Manufacturing system design is a combination of several problems and thus a complex activity. It involves solving a number of design and planning problems (Heragu, 2016). The design process structures the design activities usually in distinct phases. These phases consist of all necessary activities, from analysis to a detailed design of a selected solution for one system. Bellgran and Säfsten (2010) structure the design activities into the preparatory design and design specification phases. The former are activities concern analysis of the prerequisites and summarising them in a requirement specification for the production system to be designed. The activities during design specification are concerned with creating different solutions, evaluating these, and a detailed system solution. Figure 5.1 shows the framework of Bellgran and Säfsten (2010), where typical activities are listed by them and suggestions of other researchers (Cross, 2008; Pahl & Beitz, 1996; Roozenburg & Eekels, 1995; Ulrich & Eppinger, 2007; Wu, 1994).

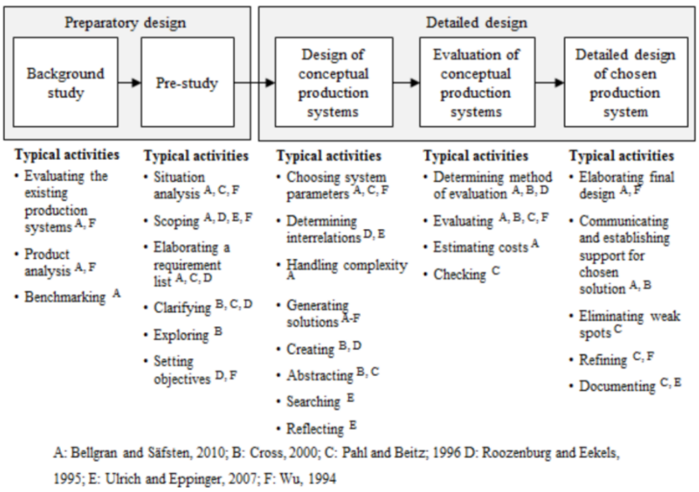


Figure 5.1: Design framework for manufacturing system design suggested by Bellgran and Säfsten (2010).

The framework discussed is of a general nature and does not indicate aspects of a subsystem and in which order they should be designed. Heragu and Lucarelli (1996) proposed a hierarchical framework for solving the design and planning problems of a manufacturing system design process. It defines aspects of the four subsystems in order. The more important design questions of their framework, given in Figure 5.2, in combination with the research scope, are process planning (e.g., defining process types and process sequence), tooling and fixture determination, the layout of the process, and material handling method. However, Heragu (2016) emphasised that the framework is by no means exhaustive, and the problems do not necessarily have to be solved in the order shown. Frequent backtracking or iterating between two or more aspects may be necessary.

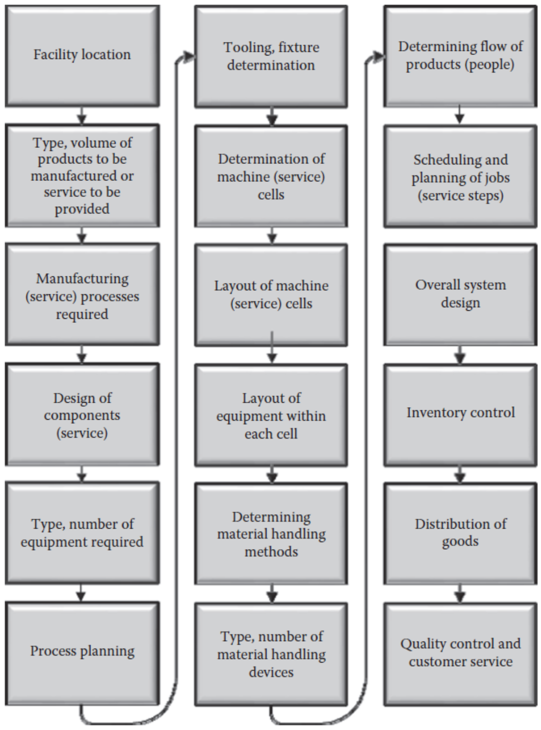


Figure 5.2: Design framework for manufacturing system design suggested by Heragu and Lucarelli (1996).

Many companies have developed frameworks to summarise their concepts and ideas about how manufacturing systems should be designed. These frameworks are often based on the principles of lean manufacturing or the Toyota production system. They generally do not explicitly distinguish between what the system is trying to achieve and how it will be achieved. Instead, these frameworks structure the application of various tools for manufacturing system design and improvement (Duda, 2000). The following two paragraphs discuss the framework based on the Toyota production system and lean manufacturing.

Toyota production system framework
The Toyota production system framework has the three goals of high quality, low cost, and short lead time at the highest level. It emphasises that a stable manufacturing process is the foundation of a proper system design. The stability of a process, the minimal process variation, is needed for achieving the three higher goals (Duda, 2000). Monden (2012) used these principles to develop a framework of the Toyota production system where tools guide the team toward the three higher goals given in Figure 5.3. The team performs the tools in the order suggested by the framework.

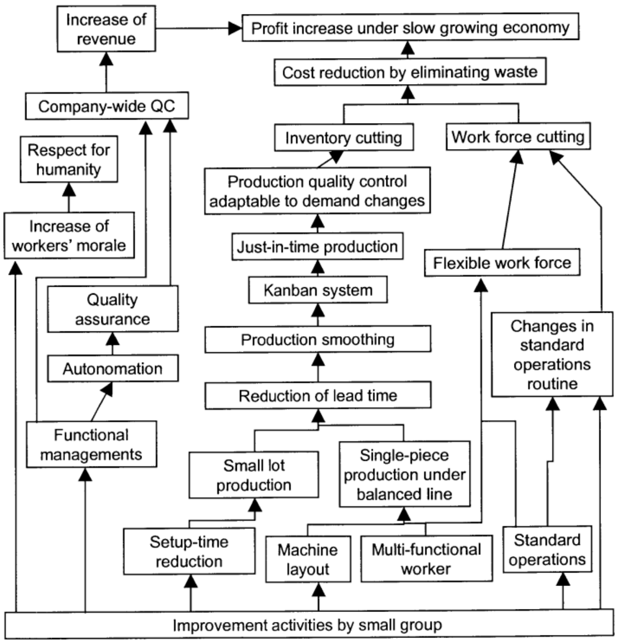


Figure 5.3: Toyota production system framework for process design suggested by Monden (2012).

Lean manufacturing framework

The lean manufacturing framework was developed by Masafumi Suzuki of TRW Automotive. It relates to the framework of the Toyota production system since it uses the pillars of the Toyota production systems: just-in-time (JIT) and jidoka. However, the lean framework specifically mentions per pillar methods or tools and relates them to the seven types of waste, shown in Figure 5.4. The solid lines indicate a strong correlation between a method or tool and a type of waste, and a dotted line indicates a weaker relationship. The high-level objective for the lean manufacturing framework is cost reduction and the improvement of productivity by eliminating waste (Duda, 2000).

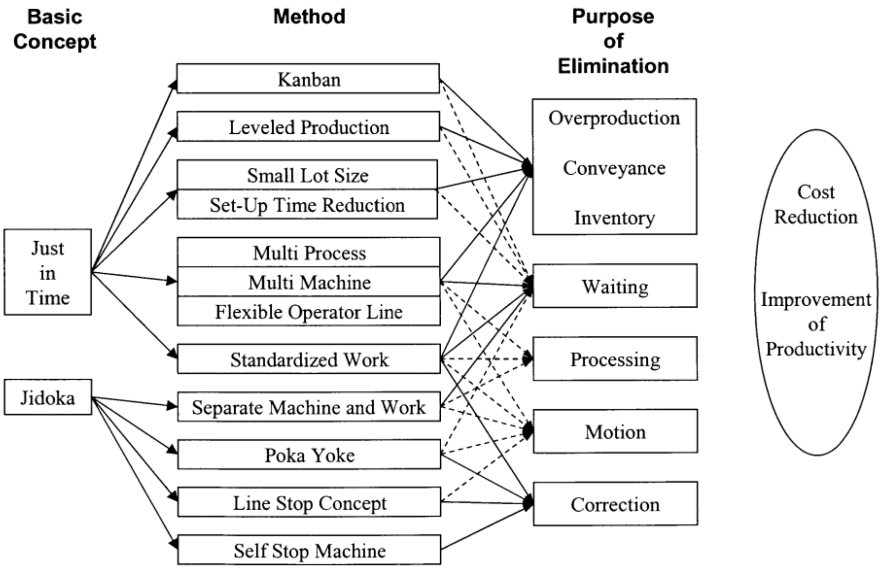


Figure 5.4: Lean manufacturing framework for process design suggested by Suzuki (Duda, 2000).

5.2 Facility layout

Facility layout is the arrangement of departments to specific locations on the floor. Departments can, for example, be workstations, offices, operating rooms, or rest areas. Hence, different types of facility layout problems exist. Heragu (2016) defined four types: service systems, manufacturing, warehouse, and non-traditional. Service systems include hospitals, insurance offices, and restaurants. Non-traditional problems occur in many other situations. Examples are the layout of a keyboard to improve keyboarding speed and the placement of semi-conductors on a chip to minimise the area required and the length of the connections.

The layout of the lever assembly is a manufacturing facility layout problem. An important consideration when designing a manufacturing layout is minimising material handling. It increases the efficiency and productivity of the manufacturing system. Heragu (2016) and Tompkins, White, Bozer, and Tanchoco (2010) also mentioned other factors influencing the facility layout, including:

- Process positioning
- Flow system

5.2.1 Process positioning

The first step in process design is the position of the process resources. The volume and variety of the product are key aspects of process positioning. They relate in that low-volume processes often have a wide variety of products, and high-volume processes often have a small variety of products. The product-process matrix illustrates the relationship between the volume-variety position of the process and its design characteristics. Different process types fit on the diagonal of the matrix, which represents the fit between the process and its volume-variety position. These five process types are project, jobbing, batch, mass, and continuous processes. Figure 5.5 shows the product-process matrix with the process types on the diagonal (Slack & Brandon-Jones, 2018).

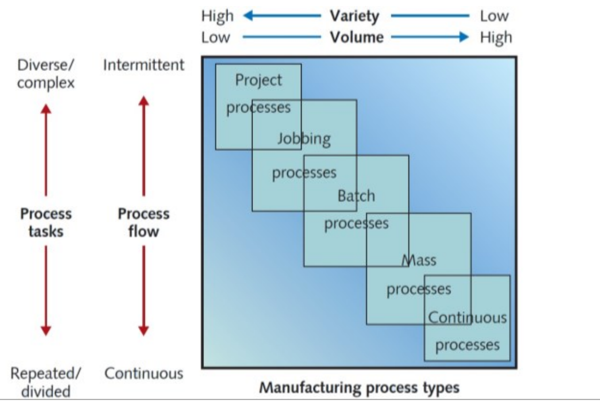


Figure 5.5: Product-process matrix with the different process types on the diagonal (Slack & Brandon-Jones, 2018).

Project processes

Project processes manufacture highly customised products. The time needed to produce the product is relatively long, as is the interval between the completion of each product. Each unit of output is usually large, with resources organised specifically for it and many activities carried out simultaneously. A typical example of project processes is shipbuilding. So, project processes are characterised by low-volume and high-variety (Pycraft, Singh, & Phihlela, 2000; Slack & Brandon-Jones, 2018).

Jobbing processes
Jobbing processes have similarities with project processes. They are characterised by low-volume and high-variety. However, each product shares the resources with many others in jobbing processes instead of all resources dedicated to one project. In addition, jobbing processes have higher volumes, a low degree of repetition, and the products are usually smaller in size. The products are typically one-offs, such as specialist tools (Pycraft et al., 2000; Slack & Brandon-Jones, 2018).

Batch processes
Batch processes produce more than one product at a time. During processing, each step of the process repeats itself as often as the batch size. Batch sizes can range from just two or three to quite large. Processing small batch sizes is almost similar to a jobbing process, whereas processing large batch sizes can be fairly repetitive. Therefore, batch processes have a wide range of variety and volume levels. Examples are machine tool manufacturing and bakeries (Pycraft et al., 2000; Slack & Brandon-Jones, 2018).

Mass processes
Mass processes have repetitive and largely predictable activities. They manufacture products in high volume with a small effective variety. The variants that affect the basic process of production are the effective varieties. A typical example of a mass process is a car factory. It produces cars in a range of colours, but the colour does not affect the production process. The colour of the car is not an effective variety (Pycraft et al., 2000; Slack & Brandon-Jones, 2018).

Continuous processes
Continuous processes operate at even a higher volume and often have a low variety. They sometimes actually are continuous and produce in an endless flow. Continuous processes characterise as relatively inflexible, capital-intensive, and highly predictable flow. The refining of oil and the production of chemicals are typical examples of continuous processes.

A process should ideally lie on the diagonal of the product-process matrix. It has lower operating costs than a process having the same volume-variety position but lies off the diagonal. Processes that lie to the right of the diagonal are more flexible than needed. The activities should be more standardised. On the other hand, processes that lie to the left of the diagonal are too inflexible and over-standardised. They lack the flexibility expected for their volume–variety position. Therefore, Slack and Brandon-Jones (2018) point out that the first step in examining the design of an existing process is to check if it is on the diagonal of the product-process matrix. The volume-variety position of the process may have changed without any corresponding changes to the process design. Thus, moving down over the diagonal of the product-process matrix reveals the change in the nature of a process. Along with its nature, the physical arrangement of resources, the layout changes. So, the product volume-variety characteristics partly determine the layout of the process. For example, a high-volume low-variety process requires a layout that can cope with the regular flow. Hence, Slack and Brandon-Jones (2018) define the general layout types fixed-position, functional, cell, and product layout. Figure 5.6 gives the product-process matrix with the layout types on the diagonal.

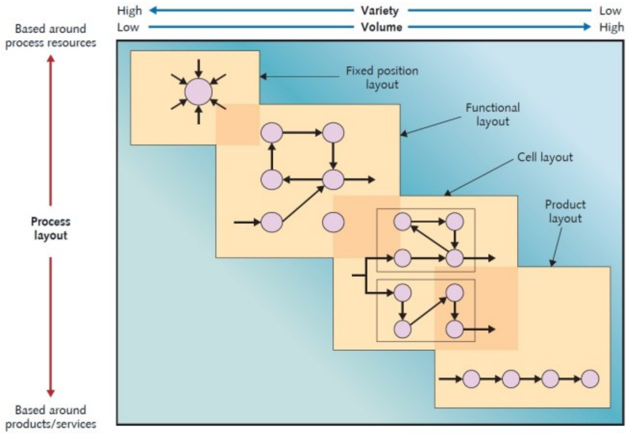


Figure 5.6: Product-process matrix with the different layout types on the diagonal (Slack & Brandon-Jones, 2018).

Fixed-position layout

In a fixed-position layout, the product does not move between the transforming resources. It may be bulky, inconvenient, or too delicate to move. Therefore, materials, equipment, and people move to the location of the product (Heragu, 2016; Slack & Brandon-Jones, 2018). This layout has as advantage that the usually bulky and expensive product does not move from place to place. Thus, the risk of product damage and the moving costs reduce. However, the relocating cost of equipment increases significantly, and the equipment utilisation is low (Heragu, 2016).

Functional layout

A functional layout also called a process layout, has machines and workstations that perform similar activities arranged together. It means that materials flow from activity to activity according to their needs. The functional layout is suitable for manufacturers producing a high variety of products in small quantities. This flexibility should increase resource utilisation (Heragu, 2016; Slack & Brandon-Jones, 2018). On the other hand, a process layout has increased material handling costs, long product cycle times and queues, complexity in planning and control, and decreased productivity (Heragu, 2016).

Cell layout

A cell layout has grouped the transforming resources dedicated to a product family into a cell. The transformed resources move to one part of the cell where their immediate processing needs are. Afterwards, processing may continue in another cell. A cell layout usually is a combination of a functional and product layout. It maintains some of the efficiency of a product layout and some of the flexibility of a functional layout. In addition, a cell layout has the advantages that it reduces material handling costs, work in process, and product lead times. However, a cell layout may require additional transforming resources and reduce the overall equipment utilisation (Slack & Brandon-Jones, 2018).

Product layout

A product layout has the transforming resources arranged in an order corresponding to the sequence in which the product undergoes its required activities. Since the transformed resources 'flow' along a line, this layout type is also called flow, line, or flow-line layout. The layout reduces material handling time and processing time and eases planning and control. Its high-volume and standardised characteristics result in a lack of flexibility. Adoption of product layout is costly and hence not suitable for products subject to frequent product design changes (Pycraft et al., 2000; Slack & Brandon-Jones, 2018).

The nature of the process, the volume-variety position in the product-process matrix, is one of the main influences on suitable layout types. It shows that there is a link between layout and process type. The layout type is just like the process type determined by the volume and variety characteristics of a product. However, two alternative layouts are usually appropriate given any process type. Table 5.1 combines process types with potential layout types.

Table 5.1: Potential layout types per process type.

Process type	Potential layout types
Project process	Fixed-Position layout Functional layout
Jobbing process	Functional layout Cell layout
Batch process	Functional layout Cell layout
Mass process	Cell layout Product layout
Continuous process	Product layout

5.2.2 Flow system

Flow systems describe the required resources (processing and transporting facilities) to create the flow of an item and the communications to coordinate the resources. Flow is the movement of goods, materials, energy, information, people, or a combination of them. A flow process is either discrete or continuous, depending on the process type. Tompkins et al. (2010) distinguished supply, manufacture, and distribution flow systems, called materials management, material flow, and physical distribution systems, respectively. The flow of materials into a manufacturing facility is a part of the materials management system. If the flow of components is within a manufacturing facility, it is the material flow system. Finally, the flow of products from a manufacturing facility is a part of the physical distribution system. Given the research scope, Section 1.4, we described that we only consider the flow of materials within the facility. Hence, we focus on material flow systems and exclude the materials management and physical distribution system.

Material flow system

An important aspect of the material flow system is determining the general flow pattern for the materials, parts, and WIP inventory, through the system. The flow pattern is the overall pattern in which the product flows from the beginning to the end as it transforms from raw material to finished product. The flow patterns may vary depending on the level of facility layout. The building is the top level. It consists of multiple departments, which in turn consist of workstations. The lever assembly is a department within hall 5A, the sheltered workshop. Therefore, we focus on flow patterns within a department.

Flow patterns within departments

The flow pattern within a department depends on the layout type of the department. The fixed-position layout is an exception. The product has a fixed location from the beginning to the end and thus has no flow pattern. The flow patterns suitable for product, functional, and cell layouts with material handling considerations are:

- Spine flow pattern
- Loop flow pattern
- Tree flow pattern
- Line flow pattern

Spine flow pattern

A spine flow pattern has a material handling device operating along the central spine. The flow in the central spine is either unidirectional or bidirectional. The workstations, located alongside the main flow line, are connected with the main flow by spurs. It is possible to have workstations on one or both sides of the spine, shown in the top left of Figure 5.7.

Loop flow pattern

In a loop flow pattern, the material handling device forms a loop around the workstations. The workstations are either situated inside or outside of the loop given in the top right of Figure 5.7. The direction of flow in the loop is unidirectional or bidirectional.

Tree flow pattern

The tree flow pattern has, just like the spine flow pattern, a central material handling device. Trees, consisting of multiple linked workstations, connect with the main flow. In the centre of the tree is another material handling device that moves the parts from workstation to workstation, illustrated in the bottom left of Figure 5.7.

Line flow pattern

The line flow pattern is the generally used flow pattern. The most basic line flow pattern is the I-flow or straight-line flow. It uses space efficiently. However, a long, straight-line flow results in a rather thin building shape, which is not the most efficient building shape. Therefore, other variants of the line flow are the U-flow, S-flow, W-flow, and O-flow, shown in the bottom right of Figure 5.7. These variants have a shorter perimeter length for the same surface area. Particularly long lines often have an S-flow and W-flow. The assembly lines in the automotive industry are an example. For assembly processes with minimal or no backtracking, the line flow structure is the most effective type of production.

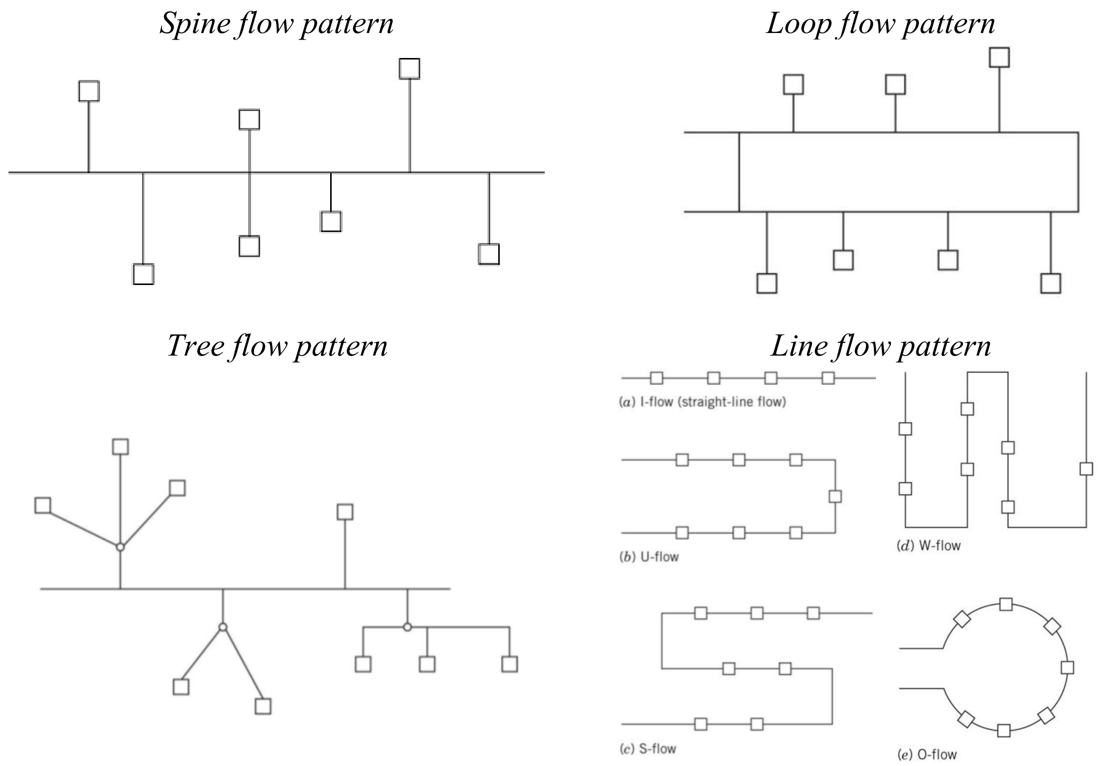


Figure 5.7: Material flow patterns with material handling considerations (Tompkins et al., 2010).

The use of a U-shaped flow over a straight-line flow is especially encouraged by lean and JIT philosophies. JIT offers principles and techniques to reduce cost by eliminating waste and improving product quality. The U-shaped line arranges the workstations in the order in which production operations take place. The operators work inside the U-shaped line. They only start working on a new product when a finished product leaves the process. Also, at most one inventory unit is between adjacent workstations, which reduces WIP. Moreover, communication among the operator improves, and interaction is possible at all stages of the process. Furthermore, the U-shaped line also offers scalability. The number of operators can increase or decrease with the demand (Tompkins et al., 2010). Finally, Miltenburg (2001) summarised the improvements of 22 successful cases where an organisation implemented a U-shaped line. On average, the productivity improved by 76%, WIP decreased by 86%, lead time reduced by 75%, and defective rates diminished by 83%.

5.3 Material supply

According to Johansson (2006), the material supply system consists of six elements: material feeding, storage, transportation, material handling, packing, and manufacturing planning and control. However, he mentioned that material handling often includes transportation within a facility. Given the research scope in section 1.4, we focus on material feeding in subsection 5.3.1, material storage in subsection 5.3.2, and production control strategies in subsection 5.3.3.

5.3.1 Material feeding modes

A material feeding mode is a method of supplying and presenting the materials to the production process (Hanson, 2012). The literature provides the following four methods of feeding the materials: continuous supply, batch supply, kitting, and sequencing. Hence, the following four paragraphs discuss every one of them. Afterwards, we select one of the operating modes and introduce potential feeding policies. Finally, we pick one feeding policy and describe its generally used transportation system.

Continuous supply

Continuous supply or line stocking stores all materials used for assembly near their point of use. These materials are sorted by part number in suitable units for handling. Often, these units are the suppliers' original packaging or the internal supplying process, resulting in no required repacking (Corakci, 2009). The replenishment of the material feeding mode is often controlled by using Kanban signals (Sali, Sahin, & Patchong, 2015). The continuous availability of stock is advantageous in case of defectives. However, continuous supply may require space-efficient part presentation or repacking when a workstation uses a large number of different components or components of large dimensions (Corakci, 2009).

Batch supply

Batch supply delivers the number of individual components corresponding to the potential demand of a batch of end products. These materials are stored near their point of use (Hanson, 2012). There is only a slight difference between batch and continuous supply in the replenishment trigger. Therefore, some researchers (Sali et al., 2015) refer to both material feeding modes as continuous supply or line stocking. They define the difference between selecting one mode on whether the materials are stored on large carriers or in small boxes or bins.

Kitting
Kitting supplies a specific assortment of components or subassemblies that are used in one or more assembly operations in kits. These kits consist of the materials required to assemble one unit of the end product and can consist of several carriers. Although kitting requires a preparation process and thus is quite time-consuming, it saves space at the assembly stations. Furthermore, kitting is particularly advantageous at assembly stations where the total number of component varieties is high. On the contrary, when the number of component varieties at an assembly station is low, kitting is less advantageous (Hanson, 2012; Sali et al., 2015).

Sequencing
Sequencing can be considered a special form of kitting. It supplies one type of component in the sequence the components are consumed at the assembly station. It is favourable when only a few components are assembled at each station. Kitting would require a lot of additional material handling to prepare these kits. Furthermore, the material feeding mode suits components of large dimensions, high diversity, and low consumption rate. The sequencing process can be performed within or outside the assembly factory, and the preparation time is the longest with respect to the other described modes (Corakci, 2009; Sali et al., 2015).

Feeding policy
The lever is a high-volume, low-variety product, meaning the material feeding modes kitting and sequencing do not suit the new production process design. Hence, we review feeding policies for continuous supply or line stocking. Baller, Hage, Fontaine, and Spinler (2020) mention four line feeding policies that suit the line stocking feeding mode. These are line side repacking, large load carrier (two-bin), large load carrier (one-bin), and small load carrier (one-bin). The first supplies components without any transport carrier. These components hang on a hook, for example. The second consists of large carriers (e.g., pallets) in a two-bin system. The third uses a one-bin system where the left-over materials of one bin are repacked on another to keep a one-bin system. The fourth uses small carriers (e.g., bins or boxes) to supply materials in a two-bin system.

Milk runs
Given the dimensions of the lever components, small carriers should be sufficient to supply a decent amount of materials to the production process. Furthermore, delivering all the lever components without using a carrier is inconvenient and could require a lot of preparation time. The continuous material stream often uses the Kanban principle for replenishment in a two-bin system. Kanban is an effective and simple system with little inventory. In addition, it is often combined with milk run deliveries (Baller et al., 2020; Hanson, 2012). Milk runs are transportation systems where materials are delivered from a central storage location to several points of use. They are performed in certain predetermined short time intervals, resulting in frequent deliveries of components in small amounts. Hence, the lead times and the inventory levels at the point of use are low (Klenk, Galka, & Günthner, 2015).

5.3.2 Material storage and inventory
The storage of materials can either be centralised or decentralised. A centralised storage location, generally a warehouse, has the advantages of a high level of inventory control, lower inventory levels, and thus costs. However, the time needed to supply the materials to the workstations is longer. Decentralised storage, generally a supermarket, stores the materials close to where they are needed as inventory. The time required to supply these materials is shorter. In addition, decentralised storage is more flexible and robust because the inventory

minimises downtime in case of, for example, quality issues. The disadvantage of decentralised storage is higher inventory levels and thus increased inventory holding costs (Battini, Faccio, Persona, & Sgarbossa, 2009; Milewski, 2020).

5.3.3 Production control

Production control regulates the flow of materials from the beginning to the end as it transforms from raw material to finished product. The literature describes several control strategies. Hence, we first describe lean manufacturing. Then, we discuss quick response manufacturing. Lastly, we mention the theory of constraints.

Lean manufacturing

Lean manufacturing focuses on eliminating waste, reducing inventory, improving throughput, and encouraging employees to bring attention to problems and suggest improvements to fix them. It uses JIT principles to pace the process at the takt time and pull or constant work in process (CONWIP) to regulate the product flow at all stages (Stump & Badurdeen, 2012). In a pull-controlled process, the downstream process step triggers the preliminary step to produce a new part. Kanban cards can regulate the flow of materials using the pull principle. They contain all the product information and the requested amount. When the requested amount is one, the process is a one-piece flow process, considered an ideal process (Tošanović & Štefanić, 2021). A one-piece flow process has no WIP, shortened lead times, and uses less space. CONWIP consists of push and pull elements to buffer variation in workload due to product and process variations (Stump & Badurdeen, 2012). It limits the maximum amount of WIP using cards. When an order is finished, the card can be assigned to a new order, pulling it into the process. In addition, when a process step is finished, the order moves to the next process step without considering the capacity (push). Hence, CONWIP better suits multi-stage processes with high-variety products (Arbulu, 2006).

Quick response manufacturing

Quick response manufacturing (QRM) focuses on lead time reduction of production processes involving high-variety products. Its lead time reduction focus yields responsiveness to the customers (Stump & Badurdeen, 2012). It requires a company to have multiple production cells on subsets of the production process. The requirements and needs of a product then determine the different cells where the product is processed. It controls the flow of material using POLCA cards. POLCA is an abbreviation of paired-cell overlapping loops of cards with authorisation. The cards are capacity cards and indicate that a downstream cell has available capacity to process more work. POLCA has push and pull elements. It authorises the beginning of the work (push), but the work cell cannot start without a POLCA card from the destination cell (pull). One card for each pair of cells remains with the product during its journey through both cells of the pair. After the second cell has finished the work, the card returns to the first cell in the pair (Suri, 2003). Figure 5.8 gives the POLCA card flows for a particular order. The QRM strategy with POLCA is a robust system and offers a high degree of flexibility for low-volume, high-variety products (Stump & Badurdeen, 2012).

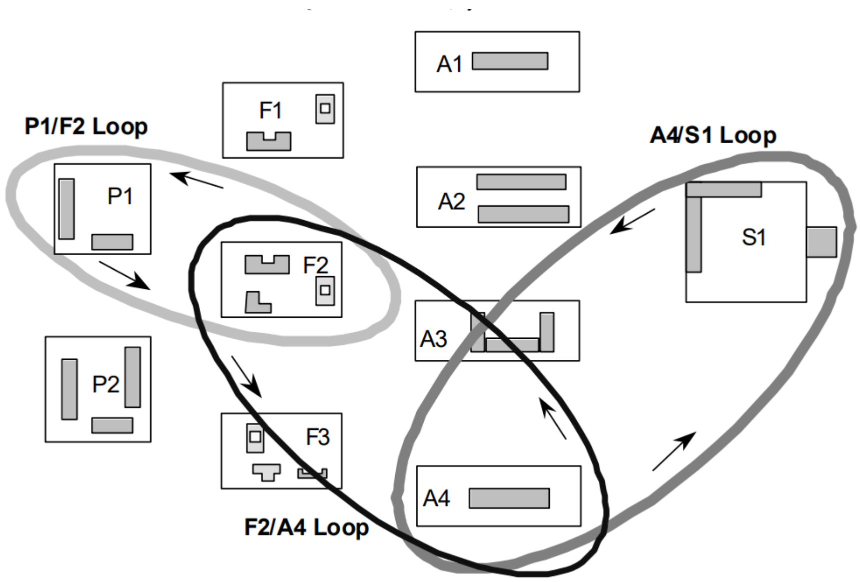


Figure 5.8: The flow of POLCA cards through the production cells for a specific product (Suri, 2003).

Theory of constraints

The theory of constraints (TOC) focuses on a constraint or bottleneck in the system. A bottleneck determines the throughput of the system. The drum-buffer-rope principle of TOC can control the process. It uses the constraint or bottleneck of the system as the drum or pacemaker of the process. Between de drum and the upstream processes is a buffer. The buffer prevents the stoppage of the constraint. In addition, the rope pulls the products from the upstream processes to the bottleneck. Figure 5.9 visualises the drum-buffer-rope principle of the TOC. Thus, the drum-buffer-rope principle provides a means of inventory control and system pacing on the shop floor (Stump & Badurdeen, 2012).

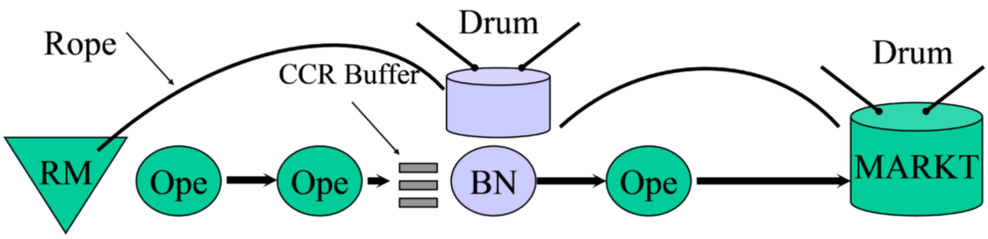


Figure 5.9: The drum-buffer-rope principle of TOC (CPC, n.d.).

Another aspect of the TOC is its continuous improvement focus on bottleneck elimination. For this purpose, Goldratt (2004) formulated five steps: identify the system’s constraint (i), decide how to exploit the constraint (ii), subordinate everything else to the above decision (iii), elevate the system’s constraint (iv), and if in any of the previous steps a constraint is broken, go back to the first step. Further detailing of this aspect of the TOC is beyond the scope of this research.

5.4 Workstation design

The new production process design of the lever consists of several workstations that we have to develop. Hence, we discuss some tools to develop the workstations and design fixtures. First, subsection 5.4.1 discusses design for assembly. Subsection 5.4.2 presents an approach to design fixtures. Then, subsection 5.4.3 introduces the methodology of single-minute exchange of die. Subsection 5.4.4 finalises this section and discusses the poka-yoke principle.

5.4.1 Design for assembly

Design for Assembly (DFA) designs the products for ease of assembly. It focuses on the number of parts, handling, and ease of assembly operation (Boothroyd, Dewhurst, & Knight, 2011). Recall from Section 1.4 that the design of the lever is not part of this research. However, DFA provides some general guidelines for manual assembly. These can be of added value for the design of the lever assembly process and, in particular, the workstation design.

Boothroyd et al. (2011) divide the process of manual assembly into two separate areas. The first is handling, where a part is acquired, oriented, and moved. The second is insertion and fastening, where a part is mated to another part or groups of parts. The following two paragraphs list the guidelines as the part being the subject. In the design process of the workstations, the part could easily be a fixture, tool, or tooling.

Design guidelines for part handling

For the ease of part handling, Boothroyd et al. (2011) list that a designer should attempt to:

- Design parts that have an end-to-end symmetry and rotational symmetry about the axis of insertion. If this cannot be achieved, try to design parts having the maximum possible symmetry.
- Design parts that, in those instances where the part cannot be made symmetric, are obviously asymmetric.
- Provide features that prevent jamming of parts that tend to nest or stack when stored in bulk.
- Avoid parts that stick together or are slippery, delicate, flexible, very small or very large, or that are hazardous to the handler (i.e., parts that are sharp, splinter easily, et cetera).

Design guidelines for insertion and fastening

For the ease of insertion, Boothroyd et al. (2011) mention that a designer should attempt to:

- Design so that there is little or no resistance to insertion and provide chamfers to guide the insertion of two mating parts. Generous clearance should be provided, but care must be taken to avoid clearances that result in a tendency for parts to jam or hang up during insertion.
- Standardise by using common parts, processes, and methods across all models and even across product lines to permit the use of higher volume processes that normally result in lower product costs.
- Use pyramid assembly. Provide for a progressive assembly about one axis of reference. In general, it is best to assemble from above.
- Avoid, where possible, the necessity for holding parts down to maintain their orientation during manipulation of the subassembly or during the placement of another part. If holding down is required, then try to design so that the part is secured as soon as possible after it has been inserted.
- Design so that a part is located before it is released. A potential source of problems arises from a part being placed where, due to design constraints, it must be released before it is positively located in the assembly.
- Avoid the need to reposition the partially completed assembly in the fixture.

5.4.2 Fixture design

A fixture locates, holds, and supports a workpiece during a manufacturing operation. It must correctly locate a workpiece in a given orientation in relation to a tool, measuring device, or another component. A fixture generally consists of locators, clamps, supports, and a fixture body. The locators constrain the movement of a workpiece, whereas a clamp exerts force to hold a workpiece securely in the fixture against external forces. Supports prevent the workpiece from deforming when it is under the influence of, for example, processing forces. Finally, the fixture body is the structural element of a fixture and maintains the spatial relationships between the locators, clamps, and supports. The advantages of using fixtures are that they eliminate positioning of the workpiece and frequent checking before machining operation starts. Thereby, it results in considerable savings in setup time. Furthermore, it simplifies the locating task and allows the replacement of skilled employees with semi-skilled employees (Nee & Tao, 2004).

Nee and Tao (2004) defined three stages in the design process of a fixture:

- Stage one is the information gathering and analysis. These include a product analysis of the design specifications, examining the processing equipment (e.g., tooling), and considering the ease of assembly and operator safety.
- The second stage involves the consideration of clamping and locating schemes. It considers the use of clamps, locators, or both to constrain the workpiece. Furthermore, what type of, for instance, locators are used, and how should they be positioned. The latter means how many degrees of freedom should the clamps or locators constrain. The scheme needs to be devised in such a way that it does not interfere with tools or tooling.
- Stage three designs the fixture body. It links all the other elements used for locating and clamping, for example, into an integral fixture. In addition, it incorporates other aspects such as selection of fixture material(s), single-minute exchange of die (SMED), and poka-yoke(s).

5.4.3 SMED

The single-minute exchange of die method consists of a theory and a set of techniques that focus on reducing the setup and changeover time of a process to less than ten minutes (Shingo & Dillon, 1985). The changeover time is the time between the last product from the previous production order leaving the machine and the first good product for the following production order (Ferradás & Salonitis, 2013). Setup times are often reduced to increase bottleneck capacity, minimise costs, and enhance flexibility. The latter is in the case when a large variety of products and varying product demands require flexibility to respond quickly to customers' needs (Van Goubergen & Van Landeghem, 2002). Especially the small-batch processes of JIT production require adequate demand responsiveness and hence a significant number of setups and changeovers (Costa, Sousa, Bragança, & Alves, 2013).

Shingo and Dillon (1985) developed SMED and categorised all setup activities into internal and external activities. Internal activities are the activities that can only be performed when the machine is stopped. External activities are the activities that can be performed during normal operations when the machine is still running. Both activity categories involve different operations such as preparation, material checks, tool changes, calibrations, and adjustments.

Costa et al. (2013) defined four distinct stages when applying the SMED methodology:

- Preliminary stage identification of setup activities.
- Stage 1 classification of activities into internal or external.
- Stage 2 convert internal activities to external activities.
- Stage 3 streamline and reduce internal and external activities.

5.4.4 Poka-yoke

Poka-yoke is Japanese for mistake-proofing. It is any mechanism in a process that helps an employee avoid mistakes. Its purpose is to eliminate product defects by preventing, correcting, or drawing attention to human errors as they occur (Premanand, Kannan, Sangeetha, & Umamaheswari, 2018). They are easy to understand and apply. Incorporating poka-yoke in a process design eliminates mistakes at the source and improves the process performance. Kumar, Dwivedi, and Verma (2016) distinguished three types of poka-yoke based on its basic functionality:

- Shutdown poka-yoke
- Control poka-yoke
- Warning poka-yoke

Shutdown poka-yoke

A shutdown poka-yoke monitors critical process parameters and shutdowns the process when it moves outside the tolerance zone. The shutdown indicates either a defective product is about to be produced or has been produced (Kumar et al., 2016).

Control poka-yoke

A control poka-yoke is a feature of, for example, a fixture that makes it impossible to produce defects or is a feature that prevents a defective product from flowing to the next process step (Kumar et al., 2016).

Warning poka-yoke

A warning poka-yoke alerts the employee about something is wrong. It indicates that the process has produced a defective product. When the operators receive such a warning, they should immediately intervene in the process and correct it (Kumar et al., 2016).

5.5 Related work

To accommodate people with disabilities requires special adaptations to eliminate barriers to access. Legislation has in many countries been a solution to improve employment among these people. However, designing products and environments that can be used by the largest proportion of the population possible avoids the need for special adaptations. This approach, called universal design, emphasises capability rather than disability. It argues that poor design causes exclusion and that design which requires a low capability threshold benefits everyone, not just the disabled (Saito, 2006). The universal design has seven core principles (Centre for Universal Design, 1997):

- Equitable use. The design is useful and marketable to people with diverse abilities.
- Flexibility in use. The design accommodates a wide range of individual preferences and abilities.
- Simple and intuitive use. The use of the design is easy to understand, regardless of the user's experience, knowledge, language skills, or current concentration level.

- Perceptible information. The design communicates necessary information effectively to the user, regardless of ambient conditions or the user's sensory abilities.
- Tolerance for error. The design minimises hazards and the adverse consequences of accidental or unintended actions.
- Low physical effort. The design can be used efficiently, comfortably, and with a minimum of fatigue.
- Size and space for approach and use. Appropriate size and space are provided for approach, reach, manipulation, and use, regardless of the user's body size, posture, or mobility.

Miralles, Marin-Garcia, Ferrus, and Costa (2010) analysed the benefits of certain operations research/management science tools in 48 sheltered workshops. They focused on best practices for production management and lean production tools. Their results indicated the importance of tidiness and cleanliness, considered the visual factory and 5S. In addition, the sheltered workshops widely applied job rotation so that workers learn different skills progressively. A suggestion also in the research of Eriksson and Ortega (2006). They mention that exposing workers to different tasks will not only increase their abilities but also improves the knowledge of the employer. The employer can better recognise the talents of each employee. However, Miralles et al. (2010) revealed that the sheltered workshops hardly use other lean tools (e.g., Kanban and SMED) because their managers are not familiar with the tools. Nevertheless, when correctly applied, the tools have a positive impact on work accessibility. Miralles, Holt, Marin-Garcia, and Canos-Daros (2011) demonstrated one of these tools: the poka-yoke. They applied poka-yokes to five workstations. It eased the tasks and offered benefits to all workers. However, not every worker succeeded in completing every task.

Technology is another approach to helping people with disabilities in production processes. Assistant technologies, such as sensorial, physical, and cognitive systems, are primary examples. We only introduce some simple examples since in-depth systems are beyond the scope of this research. The nature of the systems may be of added value for the design of the new production process. De Vries, De Koster, and Stam (2016) used a pick-by-light approach. They used bins to hold the different tools and components employees used during the assembly. A light highlighted the box from which the employees needed to pick a component or tool. Other researchers projected work instructions or other work-relevant information onto the workspace as cognitive support. The research of Korn, Schmidt, and Hörz (2013) is an example. They projected work-relevant information onto the workspace. In addition, whenever the employee had finished a process step, they could press a button to receive the information for the next step. Some other systems provided real-time feedback (Funk, Mayer, & Schmidt, 2015) or provided the employee with visual or audio feedback (Drolshagen, Pfingsthorn, Gliesche, & Hein, 2021).

5.6 Conclusion

The fifth chapter discussed the literature relevant to this research. It first presented several frameworks for manufacturing system design. Then, we described the relevant aspects of the facility layout. We discussed several aspects of the material supply. Subsequently, we mentioned tools and principles to develop the workstation and design the fixtures. We finalised the chapter with work related to this research. Hence, this chapter answered the fourth research question: *"What literature is available that relates to the main research question?"*

The literature review discussed four frameworks for designing a manufacturing system design, where two are approach-based and two are tool-based. The positioning of the process in the product-process matrix and the material flow through the system influence the facility layout. For this purpose, we described the five process types (i.e., project, jobbing, batch, mass, and continuous processes), four layout types (i.e., fixed-position, functional, cell, and product layout), and four material flow patterns (i.e., spine, loop, tree, and line pattern). In developing the material supply for the new process design, the relevant aspects are material feeding mode, (de)centralised storage, and production control strategy. We already excluded the unsuitable feeding modes based on the product characteristics of the lever, which left continuous supply. The discussed production control strategies were lean manufacturing, QRM, and TOC. To design the workstations, we listed several guidelines originating from DFA. The development of the fixture for the workstations uses a three-stage approach (i.e., product analysis, clamping and locating schemes, and fixture body design), where we can incorporate SMED and poka-yoke to realise fast changeovers and reduce product defects, respectively. The related work listed seven core principles for designing production processes to better include disabled workers. Furthermore, we discussed several tools and technologies researchers used to improve the inclusion of disabled people in production processes. They are mostly of a visual nature and offer the best cognitive support for the employees during production.

The literature review provided frameworks, methods, principles and techniques that we can use in the redesign of the lever assembly process. Therefore, the research continues in Chapter 6 by developing a new production process design for the lever.

6 Process redesign lever assembly

The sixth chapter redesigns the new production process of the lever as follows. Section 6.1 selects the framework to follow the design process and lists the requirements of VMI for the process design. Subsequently, Section 6.2 discusses the process planning. Section 6.3 selects the tooling and evaluates potential process layouts. Then, Section 6.4 details the material supply for the lever assembly process. Section 6.5 designs the workstations in more detail. Afterwards, Section 6.6 introduces a concept for continuous quality improvement. Section 6.7 includes ergonomics in the process design to improve working conditions. Thereafter, Section 6.8 presents a scheduling approach for the new process design. Section 6.9 selects the final layout and further details the process. Then, Section 6.10 identifies and evaluates the potential safety risks of the new process design. Lastly, Section 6.11 finalises the chapter by summarising the main aspects of the production process design of the lever.

6.1 Design framework and list of requirements

The production process redesign starts by selecting a suitable framework to design the lever assembly process in subsection 6.1.1. Afterwards, subsection 6.1.2 lists requirements of VMI to consider when designing the new process.

6.1.1 Framework

The literature review discussed multiple frameworks to design a production process in section 5.1. We adopt the framework suggested by Heragu and Lucarelli (1996) to design the lever assembly process, given in Figure 5.2. It is a comprehensive framework that includes all aspects we need to cover for the new production process design of the lever. The other frameworks are too general and miss relevant aspects such as process planning, material supply, and scheduling. However, we do not need to cover all aspects of the selected framework. An example is the facility location. The facility location of VMI is fixed and is not likely to change. Therefore, the starting point in the framework is process planning.

6.1.2 List of requirements

VMI has requirements for the new process design of the lever. We split them into fixed and variable requirements. In addition, we consider the seven design core principles listed in Section 5.5 throughout the design process. We first list the fixed requirements and afterwards the variable requirements.

Fixed requirements

The new production process design has to satisfy the fixed requirements. Otherwise, it does not fulfil prescribed requirements. VMI formulates the following fixed requirements for the production process design of the lever:

- The process design increases the capacity of the process by at least 15%.
- The process design can assemble all standard levers and clip bar levers.
- The process design fits within the current dimensions of 15x7 metres.
- The process layout includes an inbound/outbound storage location.
- The sheltered workshop is relieved from the control of inventory.
- The inventory is sufficient to assemble 150 levers.
- The tugger trains transport finished levers from the hall.
- Use the currently available transport carriers.
- The process design ensures safe working conditions.
- The weight of bins decreases below 23 kilograms.

Variable requirements

The variable requirements improve the process design and contribute to better process performance. VMI lists the following variable requirements for the production process design:

- The process design is flexible to cope with the variability in the workload.
- The process design offers perspective to include the truck tyre levers.
- The process design is simple and intuitive to use for the sheltered workshop employees.
- The process design is equitable and flexible in use for a range of individual abilities.
- The process design uses visual management to communicate information.
- The process design minimises (quality) hazards and the adverse consequence of accidental or unintended actions.
- The repair of rejected levers is not a standard operational activity.
- The number of fixtures and tools per process step is preferably one.
- The fixtures and tools are available on the spot where needed.
- The walking distance to complete one lever is as short as possible.
- The process design uses the smallest floor area possible.

6.2 Process planning

The starting point in the redesign of the lever assembly process is process planning. It starts by positioning the lever product characteristics in the product-process matrix in subsection 6.2.1. Subsequently, subsection 6.2.2 selects a material flow pattern for the process design. Subsection 6.2.3 determines a production control strategy to regulate the product flow. Afterwards, subsection 6.2.4 lists the new assembly sequence after introducing two new assembly methods and two design changes.

6.2.1 Process positioning

The literature review discussed in subsection 5.2.1 that the design of a process starts with process positioning. Process positioning uses the volume and variety characteristics of a product to determine a suitable layout and process type. The lever is a high-volume, low variety product, and its effective variety is three (i.e., standard levers, mechanical, and vacuum clip bar levers). When we position the current process design of the lever in the product-process matrix, Figure 6.1, it lies to the right of the diagonal. It is too flexible, and the activities require more standardisation. To put the process design on the diagonal, we position it in the overlapping area of mass and continuous processes, shown in Figure 6.1. The process tasks of the lever assembly are repetitive, and it would be against the volume and variety characteristics to position it as a batch process. Furthermore, the resulting highly standardised batch process requires even more material handling than the current process already endures.

The layout types corresponding to the position of the lever assembly in the product-process matrix are the cell and product layout. It means that three combinations of process and layout types are possible, as Table 5.1 lists. However, the process design becomes a mass process with a product layout. It has the flexibility required to accommodate the product varieties, a fixed requirement in subsection 6.1.2. A continuous process generally dedicates its resources to one product variety. Moreover, a product has some flexibility to handle some product varieties and simultaneously has a highly standardised characteristic, which reduces material handling and processing time. Also, the combination of a mass process with a product layout offers the perspective for the earlier excluded truck levers mentioned in subsection 2.5.1. The process design may suit these levers as well, a variable requirement.

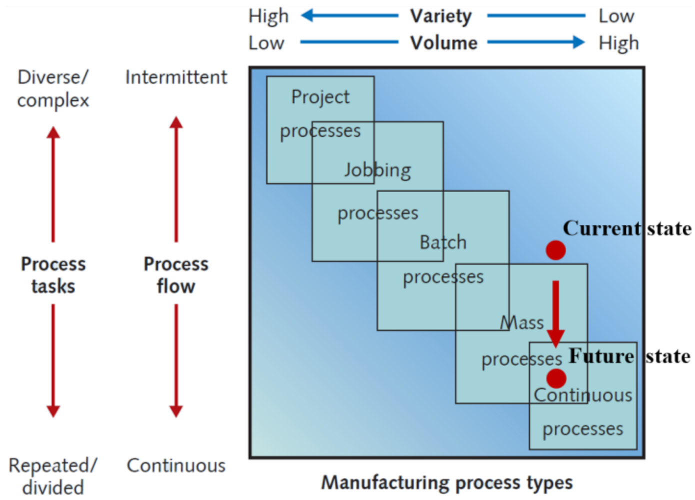


Figure 6.1: Product-process matrix with the current state and future state position of the lever assembly (Slack & Brandon-Jones, 2018).

6.2.2 Material flow pattern

The line, loop, spine, and tree material flow patterns suit a product layout while considering material handling. However, not every flow pattern is as suitable for the lever assembly. The loop, spine, and tree options are convenient for a process with backtracking. However, the lever assembly currently does not have any backtracking and does not need it. The design requires a flow pattern that minimises material handling, a major outcome of the interrelationships diagram in subsection 4.3.3. A line flow pattern can minimise the distance materials and people travel. Hence, it reduces material handling costs and improves the efficiency and productivity of the process. Therefore, the materials will follow a line flow in the process design. However, we evaluate in Section 6.3 which variant of the line flow (e.g., I-flow, O-flow, or U-flow) we can use. Factors such as production control, tooling, available floor space, material supply, and workstation design impact the layout.

6.2.3 Production control strategy

Subsection 5.3.3 discussed several production control strategies to regulate the product flow from the beginning to the end as it transforms from raw material to finished product. These strategies differ in objective and application. A suitable production control strategy for the process design of the lever is lean's JIT principles. The lead time reduction focus of QRM and its use of POLCA to control the flow of materials suits especially multi-stage processes where customisation and varieties are high. However, the lever is a low variety product and is a single-stage process. The TOC lets the process bottleneck determine the pace of the process and focuses on increasing bottleneck capacity. However, we are designing a new process and not increasing the capacity of the bottleneck in an existing assembly process. The application of TOC is a logical step after the first results outline the future performance. Therefore, we exclude QRM and TOC as suitable production control strategies and focus on selecting one of the JIT principles to control the product flow in the next paragraph.

JIT offers pull and CONWIP as principles to control the material flow in the process. CONWIP combines push and pull elements to balance the workload. Similarly to POLCA, it suits multi-stage processes with a wide variety of products better. Hence, CONWIP does not align with the future state lever assembly. Fortunately, controlling the assembly process using the pull principle is suitable. So, the new assembly process controls the material flow as components transform into a finished lever using the pull principle of JIT.

6.2.4 Assembly sequence

The literature review mentioned in subsection 5.3.3 the ideal production process is a one-piece flow process. Hence, the lever assembly ideally becomes a one-piece-flow process. However, it currently consists of two parallel processes, mentioned in subsection 4.2.3. The glueing of the pivot blocks is a separate process due to the cure time of the adhesive. Fortunately, we see opportunities to merge the two parallel processes into a one-piece-flow process. Therefore, we suggest changing the assembly method to fasten the bush bearings in the pivot block differently in the first paragraph. In addition, we propose a new assembly method to join the lever base to the pivot block in the second paragraph. Then, we present two design changes to the slide blocks in the third paragraph. Finally, we list the new assembly sequence in the fourth paragraph. Section O.1 to Section O.3 in Appendix O discuss the new assembly methods and the design changes in more detail.

Pressing bush bearings into pivot block

The new assembly method presses the bush bearings into the pivot block, depicted in Figure 6.2. It replaces the current three steps (i.e., ultrasonic cleaning, assembly, and curing) with one and allows the merging of the two parallel processes into a one-piece-flow process. Furthermore, the new assembly method reduces the workload, simplifies the assembly tasks, and improves working conditions (a fixed requirement in subsection 6.1.2). The latter improves since the adhesive and ultrasonic fluid become redundant. They are hazardous substances, and the fumes of the adhesive are carcinogenic in case of prolonged exposure.

. We discuss the new assembly method in more detail in Section O.1 of Appendix O.

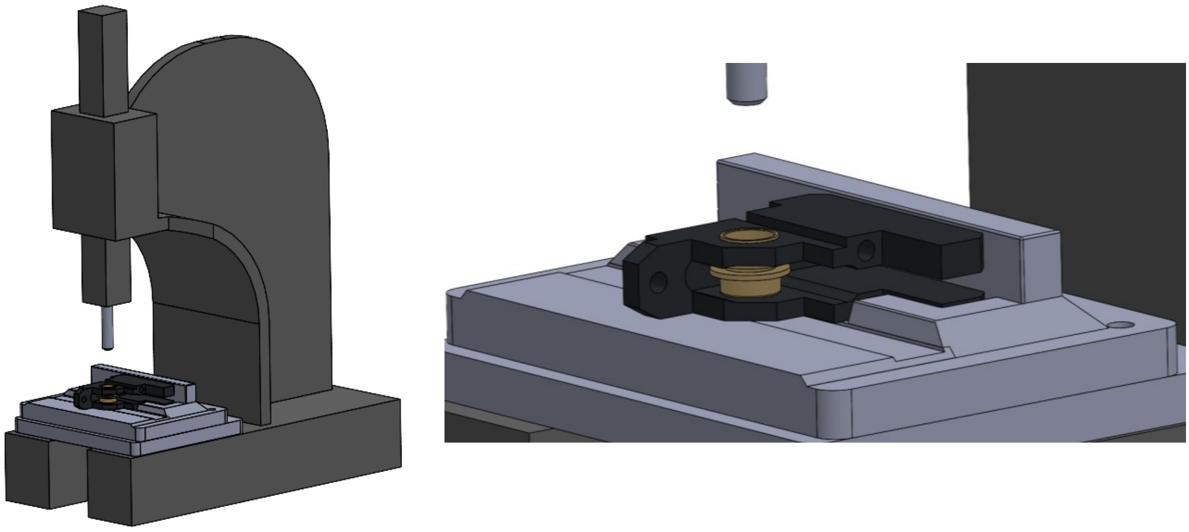


Figure 6.2: New assembly method to press the bush bearings into the pivot block.

Pressing dowel to join lever base to the pivot block

The second new assembly method replaces the fourth assembly step in the current process. It is the assembly step where % of the performed repairs in the baseline performance originate. The new method joins the lever base to the pivot block using a press instead of hammering, as Figure 6.3 visualises. The new assembly method ensures safe working conditions, a fixed requirement, and likely improves the process quality, a variable requirement. Furthermore, it reduces the assembly time and eases the assembly. Section O.2 in Appendix O elaborates on the new assembly method.

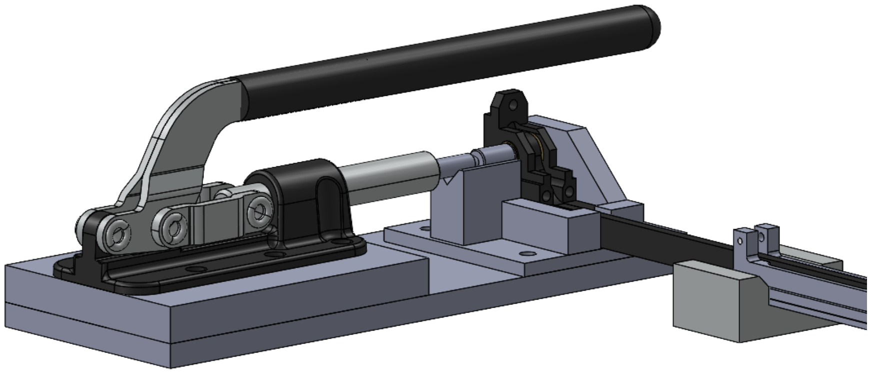
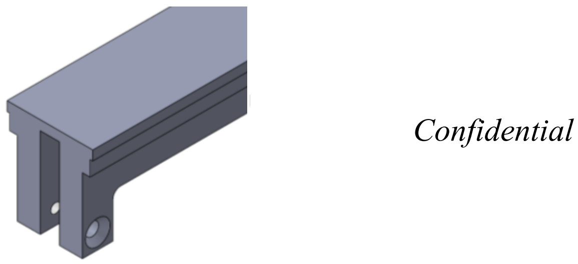


Figure 6.3: New assembly method to join the lever base to the pivot block by pressing the dowel into the pivot block.

Design change of slide blocks

Although design changes are not within the research scope, they constitute a great opportunity. So let us briefly discuss them. The design change of the slide blocks reduces the workload by half and makes two components redundant. It allows to 'scoop' the lever into the slide block. Detailing the design resulted in a component price equal to the current price. Its design is in the second picture of Figure 6.4, which also shows the current design in the first picture and the intended assembly method in the third picture. Furthermore, we recommend replacing the remaining screw with a tuflok screw, given in Figure 6.5. Using tuflok screws slightly reduces the assembly time and eliminates the use of adhesive. The latter ensures safe working conditions, which is a fixed process requirement. We describe these design changes in more detail in Section O.3 of Appendix O. However, before implementing the design changes, we first need to determine if they are technically feasible. Hence, several activities should be carried out before implementation, mentioned in more detail in the implementation plan in subsection 8.1.3.



(1) (2) (3)

Figure 6.4: Design change of the slide block, current design (1), design proposal (2), and intended assembly method (3).

Figure 6.5: Tuflok screw, where the blue nylon coating has the retaining function (Kerbkonus, n.d.).

Assembly sequence lever assembly

The design changes and new assembly methods impact the current assembly sequence (listed in subsection 2.5.2). The lever assembly becomes a one-piece flow process with the following assembly sequence:

1. Pressing bearings
2. Pressing rolls
3. Mounting slide block
4. Pressing bush bearings
5. Joining lever base to the pivot block
6. Creating a set of clip bars (*clip bar levers only)*

The first two assembly steps correspond to the current assembly sequence. The potential design change of the slide block places its assembly step before pressing the dowel. Finally, before employees can press the dowel into position, the pivot block needs bush bearings. Hence, we place it between mounting the slide block and joining the lever base to the pivot block.

6.3 Process layout

At a high level, the new production process design of the lever is finished. The next phase details the design, starting with the process layout. In the framework of Heragu and Lucarelli (1996), the steps determination of tooling type and the process layout represent detailing the facility layout. Therefore, subsection 6.3.1 discusses the selection of tooling for new process design. Then, subsection 6.3.2 presents the results of the evaluation of four potential layouts, and it excludes unsuitable layouts for the new process design.

6.3.1 Tooling selection

The next step in the redesign process is the selection of tooling. Previously subsection 6.2.4 already proposed two new assembly methods that Engineering approved for testing. Therefore, prototypes of these methods are a part of the new process design. What remains is to determine the tooling for the first three assembly steps of the new assembly sequence.

The first and second assembly steps currently press the bearings and the rolls into the lever using manual presses. Using manual presses also in the new process design seems logical. The workload should not cause any health complaints, a finding of the baseline performance subsection 3.3.4. Moreover, the presses suit the tasks for which the employees use them. Every process step requires a press due to engineering fits and the flaring of components. In addition, every process step obtains its dedicated press. It breaks the larger assembly steps down into the required small manageable tasks for the employees. Currently, not every process step has dedicated tooling, discussed in subsection 2.5.2. Therefore, the first and second assembly steps each consist of three manual presses in the new process design.

The third assembly step mounts the slide block to the lever. The tooling the employees only use is a calibrated pneumatic screwdriver. We do not alter the tooling of this assembly step. It is easy to operate, suits the task, and we do not see any potential for further improvement. Finally, when the design change of the tuflok screws is technically feasible, the employees still use it. So, the tooling for the third assembly step remains the calibrated pneumatic screwdriver.

We have selected the tooling used for the new process design of the lever assembly. Table 6.1 lists the tooling used per assembly step. The next step is to start placing the tooling in potential layouts of the new process.

Table 6.1: Tooling used per assembly step in the process design of the lever.

<table>
<tr><th>Assembly step</th><th>Tooling</th><th>Assembly step</th><th>Tooling</th></tr>
<tr><td rowspan="3">1. Pressing bearings</td><td>Press 1 – Bearing shaft</td><td>3. Mounting slide block</td><td>Pneumatic screwdriver</td></tr>
<tr><td>Press 2 – Ball bearings</td><td></td><td></td></tr>
<tr><td>Press 3 – Flaring shaft</td><td>4. Pressing bush bearings</td><td>Press 7 – Bush bearings</td></tr>
<tr><td rowspan="3">2. Pressing rolls</td><td>Press 4 – Bush roll</td><td></td><td></td></tr>
<tr><td>Press 5 – Shaft roll</td><td rowspan="2">5. Joining lever base to the pivot block</td><td rowspan="2">Press 8 – Dowel</td></tr>
<tr><td>Press 6 – Flaring shaft</td></tr>
</table>

6.3.2 Layout evaluation and exclusion

The flow the materials follow in the new process design is the line flow, discussed in subsection 6.2.2. However, we left which variant of the line flow (e.g., I-flow, O-flow, or U-flow) open. By determining the production control strategy, the assembly sequence, and the tooling, we can start outlining potential layouts of the process. For this purpose, we study variants where the materials follow an I-flow, L-flow, O-flow, and U-flow. Figure 6.6 gives an impression of the different layouts. The centre-to-centre distance between the workstations is 0.7 meters, slightly smaller than the human average step length (Frothingham, 2018). A shorter distance leaves too little room for the employees to manoeuvre side by side with ease and a larger distance only adds additional wasteful meters. We evaluated the layout variants using the criteria communication and overview, line balancing, and walking distance. Appendix P elaborates on the evaluation, and Table 6.2 lists the main properties per layout variant.

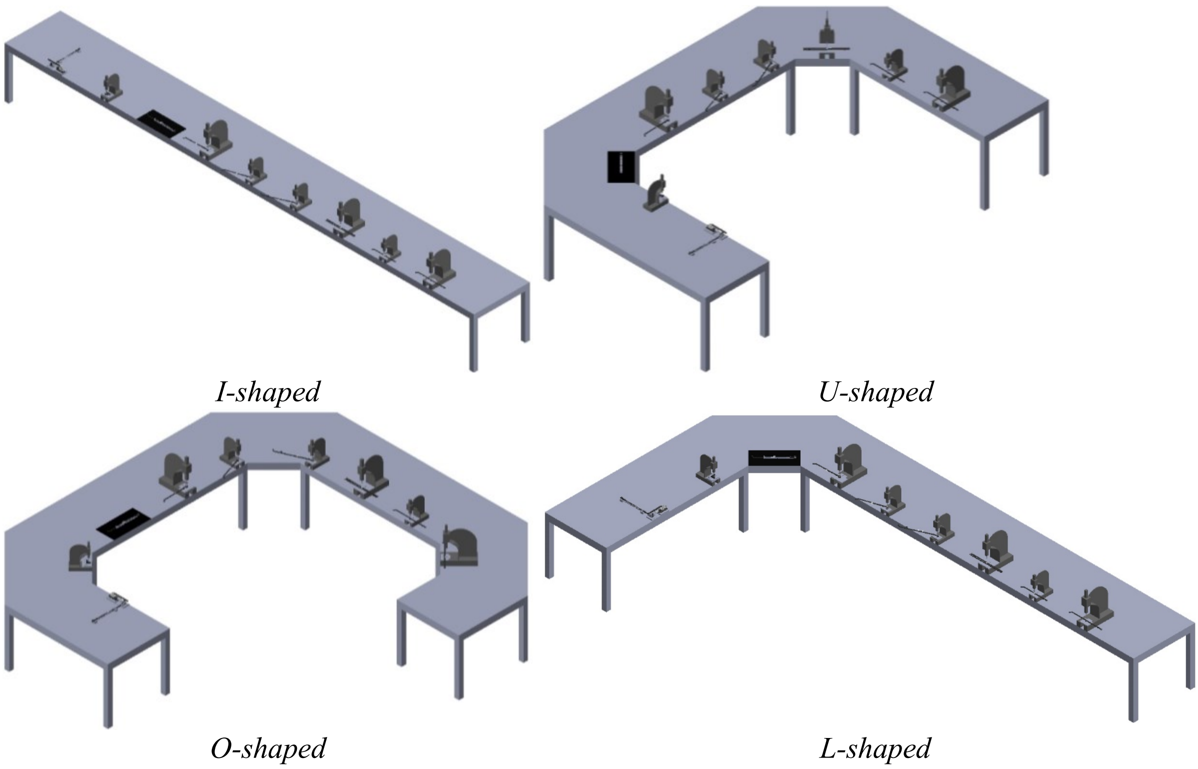


Figure 6.6: Visualisation of the levers assembly in an I-shaped, L-shaped, O-shaped, and U-shaped layout.

Table 6.2: Assessment scores of the different layout variants on the aspects of communication and overview, floor area, line balancing, and walking distance.

Layout variant	Distance most distant workstations [m]	Number of neighbouring workstations	Walking distance [m]		
			Assembly	Final to first workstation	Total
I-shaped	7.0	1-2	7.0	7.0	14.0
L-shaped	5.5	1-2	6.7	5.5	12.3
O-shaped	4.0	4-6	6.7	3.8	10.5
U-shaped	3.6	4-6	6.5	3.5	10.0

The first evaluation of the potential layout variants justified excluding the I-shaped and L-shaped layouts based on the formulated fixed and variable requirements in subsection 6.1.2. Their arrangement of the workstations is not close enough for effective communication and overview. Furthermore, their potential for line balancing is limited due to the limited number of neighbouring workstations. Lastly, the distance employees would walk to assemble one lever far exceeds the walking distance at the O-shaped and U-shaped layout. The O-shaped and U-shaped layouts have alike scores in communication and overview, line balancing, and walking distances. Therefore, after further detailing the process design, we evaluate the two remaining layout variants once more on the required floor area, safety, and integration of material supply. The latter is the next aspect of the process design we detail.

6.4 Material supply

The selection of the pull principle to control the flow of materials in the assembly process also means a pull-controlled material supply. For this purpose, we have to elaborate on different aspects of the material supply. First, subsection 6.4.1 discusses the inventory control system that manages the physical and ERP inventory. Subsection 6.4.2 elaborates on exceptions in the inventory policy. Afterwards, subsection 6.4.3 introduces parts presentation and a colour scheme to support the employees in the assembly process. Subsection 6.4.4 discusses the supply of components to the new process design. Finally, subsection 6.4.5 selects a type of transport carrier to transport the finished levers by tugger train.

6.4.1 Inventory control system

Kanban of JIT manufacturing is a simple, effective, and visual system to obtain a pull-controlled inventory system. In particular, the two-bin Kanban system mentioned in subsection 5.3.1 is suitable for the new process design. The lever has components of small dimensions, the number of variants per component is mainly low (Table C.5 in Appendix C), and the required inventory levels are low. These three arguments offer the possibility to store them in the assembly process. It eliminates the repetitive cycles of collecting and storing materials in the shelf racks, discussed in subsection 4.2.1. Another advantage is that an empty bin is the signal or Kanban for replenishment. It replaces the two processes that currently control the inventory levels, as mentioned in subsection 4.2.2. Hence, it relieves the employees of NVA activities. Also, the physical control of the inventory limits the number of components waiting, which reduces the lead time. Subsection 6.4.4 discusses the organisation of the material supply in more detail. However, one bin contains components to assemble 150 levers equal to required inventory levels. This part of the physical inventory control no longer pushes the materials in large quantities into the process. In addition, the reduced inventory levels (water level) reveal the issues (rocks) the employees currently encounter better. So, the two-bin Kanban system is the pull-controlled inventory system for the lever assembly.

The two-bin system limits the inventory in the process. However, we also need a system to deduct consumed inventory. Fortunately, it is already partly in place. The lever varieties in high demand use backflush. Backflush automatically deducts inventory when the warehouse reports that they have finished picking a PO. In practice, the deduction is immediately due to the inventory levels in the shelf racks. We also adopt backflush in the new inventory control system. However, we extended it to all lever varieties. Hence, backflush deducts inventory in the ERP system when the warehouse has completed order picking and before assembly has started. It does not have any consequences for the inventory in the process. The two-bin system remains controlling the physical inventory through Kanbans. In addition, these two independent control systems help monitor discrepancies between the virtual and physical inventory better. Every returning bin offers the opportunity to check for discrepancies. So, backflush deducts consumed inventory in the ERP system.

6.4.2 Inventory

The two-bin Kanban system places the components in the process. However, we exclude the components lever and slide block from placement in the process. The combination of both makes the lever assembly unique. Together these components have 37 varieties (Table C.5 in Appendix C). Hence, placing them in the process would require vast amounts of space. So, we decide to store the lever and slide block close to the process. However, it is not necessary to have every variety in inventory. The annual demand for some levers varieties is very low, given in Table Q.1 and Table Q.2 of Appendix Q. Other lever varieties do not necessarily have low demand but have an intermittent demand of, for example, only three POs per year, listed in Table Q.3 of Appendix Q. Thus, storing the levers and slide blocks for the 14”-18”-L495, 14”-18”-L495 (M), and 19"-24"-L493 levers is a logical decision. It covers % of the quantities, the volume fill rate, and % of the orders, the fill rate. However, no requirement specified the desired volume fill rate or fill rate. Therefore, Table Q.4 and Table Q.5 in Appendix Q outline which levers and slide blocks become inventory to achieve usual volume fill rates and fill rates, respectively. Nevertheless, we decide to add the lever and slide blocks for the 19"-24"-L493 (M). It is a practical decision, not fill rate driven. The current standard drum configuration consists of standard levers (Figure C.2 in Appendix C) and mechanical clip bar levers (Figure C.3 in Appendix C). Adding these components to the inventory means that the employees can always assemble the levers for two drum configurations. It also raises the volume fill rate to % and the fill rate to %. We still use the two-bin Kanban system, but these varieties have more than two bins. The number of levers per bin reduces, discussed in more detail in 6.7.2. In addition, the two separate supply streams still use backflush. It remains able to deduct consumed inventory. The supply of the levers and slide blocks for the other lever varieties match demand to prevent components from waiting. So, the levers and slide blocks for the 14”-18”-L495, 14”-18”-L495 (M), 19"-24"-L493, and 19"-24"-L493 (M) levers are standard inventory.

6.4.3 Part presentation

We use small flow racks to present the components in the process. They can have two or three levels to accommodate more component varieties. The top-level(s) are set under an angle to create flow when an employee removes a bin. To collect the empty bins, the employees put them on the bottom level of the flow rack. The drawback of placing the components in the process is that it possibly confuses the employees. To support them in picking the right components, we use lids and introduce a colouring scheme. The lids cover the components not used during the assembly. The colour scheme originates from the literature review. Section 5.5 describes that the best cognitive support for the employees is of a visual nature. The colour scheme consists of only four colours due to a limited number of component varieties (Table C.5 and Table C.6 in Appendix C) and excluding the levers and slide blocks from the process. The inch size range of the lever (i.e., 12”-13”, 14”-18”, and 19”-24”) for which the component is used defines the first three colours. The final colour is green and represents components used in every lever variety. Figure 6.7 gives an example. The bushes, shafts, and rolls come in three varieties (lever inch size range). Hence, the 12”-13” bin is red, the 14”-18” bin is blue, and the 19”-24” bin is yellow. Figure 6.8 gives an impression of the bin flow racks, including the colour scheme for the new process design.

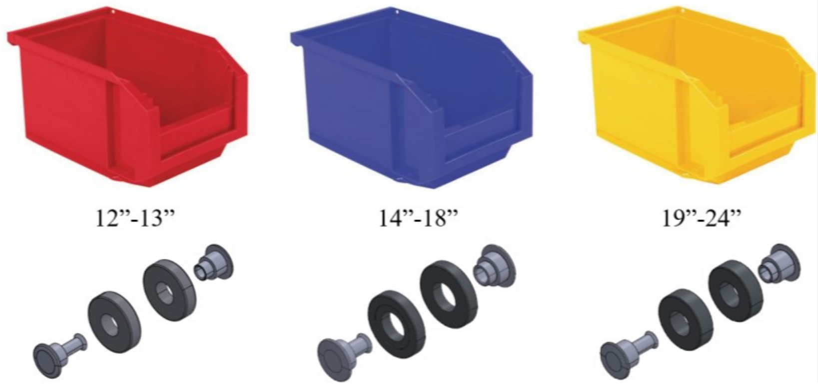


Figure 6.7: Example of the colour scheme for the bushes, shafts, and rolls.

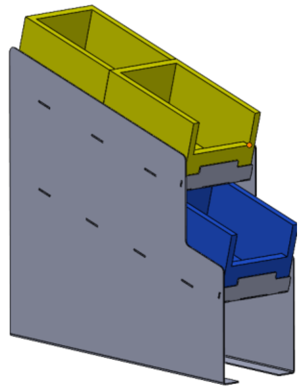


Figure 6.8: 3-level bin flow rack.

To store the levers and slide blocks, we use a decentralised flow rack. It houses the standard inventory for the four lever varieties, determined in subsection 6.4.2, in dedicated locations. Also, it has five locations, representing a weekly schedule, for the other lever and slide blocks. Subsection 6.8 discusses this aspect in more detail. The concept is that a bin located in 'today' triggers the employees to start assembly. The MPS determines the weekly schedule, as is already the case. It orders the warehouse to pick (backflush) and supply the components to production group E720. Moreover, the flow rack has locations to store the empty bins, which return to the warehouse for either replenishment or storage. Figure 6.9 gives an impression of the flow rack. It also incorporates the colour scheme. The employees know which components they need for assembly.

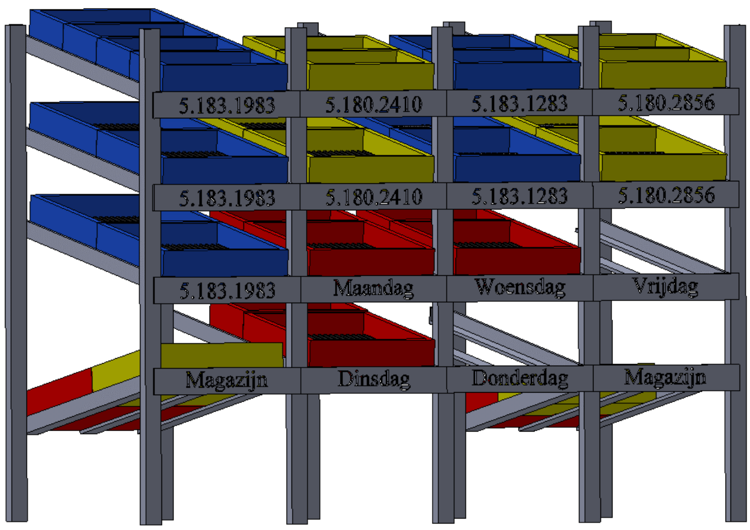


Figure 6.9: Visualisation of the flow rack for levers and slide blocks including the colour scheme.

6.4.4 Component supply

Milk runs supply the components from the warehouse to the assembly process and vice versa for empty bins. The literature review discussed the basic concept of milk runs in subsection 5.3.1. VMI already uses milk runs for the same purposes in the drum workshop. On a daily basis, an employee of the warehouse walks along flow racks to collect empty bins. The bins return to the warehouse, are refilled, and during the next milk run, the employee places them in their corresponding location. The drum workshop is in hall 5C, the same facility as the sheltered workshop in hall 5A. Therefore, extending the milk run to the lever assembly is feasible. The warehouse employee does not have to travel an additional disproportionate distance. Furthermore, it is easy to implement since VMI already uses the method. Lastly, the sheltered workshop employees perform less material handling, which improves productivity. They no longer have to place the components in neither the shelf rack nor the flow racks. So, in the new process design of the lever, the warehouse collects empty bins from the flow racks in and next to the process, refills them, and places full bins in their corresponding location: milk runs

6.4.5 Transport carrier

The final aspect of the material supply is the selection of a transport carrier. These carriers hold the bins with finished levers. Currently, the tugger trains collect the finished levers weekly. However, they drive several times a day through the hall and generally have the capacity available to bring transport carriers back to the warehouse. So, using the tugger trains to transport the finished levers daily is feasible and meets a fixed requirement listed in subsection 6.1.2. The transport carriers suitable for the tugger trains are euro pallets, steel pallets, and trolleys, given in Figure 6.10. Euro pallets have the capacity for multiple layers of bins but are not convenient. One pallet on a wheeled support frame has a limited height. Placing a bin on a euro pallet does not contribute to good ergonomics. The steel pallets have posts and are stackable. They also have a lot of capacity but require 50% more floor area than a euro pallet. The trolley can only hold four bins but requires altering the configuration of the trolleys. The latter would create a trolley version only suitable for the lever assembly. Hence, it also becomes a challenge to keep both versions separate since VMI has a lot of trolleys. So for convenience in logistics and better ergonomics, the steel pallets are the transport carriers to collect the finished levers.

Euro pallet *Steel pallet* *Trolley*

Figure 6.10: Transport carriers suitable for the tugger trains.

The tugger trains transport the steel pallets to the warehouse. Upon arrival, there currently is a complex procedure (e.g., inspection, storage, and forwarding) different for project-based and non-project-based POs. The new organisation of the material supply offers the opportunity to improve the process after the collection of finished levers. However, this part is out of the research scope. Therefore, we recommend altering the process upon finished levers arrive in the warehouse. Section 9.3 mentions some concepts consider.

6.5 Workstation design

Detailing the workstations is the next phase in the design of the lever assembly process. It starts with developing fixtures for every step that uses a manual press in subsection 6.5.1. Then, subsection 6.5.2 discusses the design process of the pressing tools for these presses.

6.5.1 Fixtures

Fixtures locate, hold, and support the workpiece during assembly. To design them for the assembly process, we use the three-stage approach suggested by Nee and Tao (2004) in subsection 5.4.2. The first stage, the product analysis, yields that every process step needs multiple fixtures due to the geometry of the components. For example, the three roll varieties differ in outer diameter, height, and hole diameter. Hence, accommodating all the rolls in one fixture is impossible. Table 6.3 lists the number of fixtures per process step and their applicability to lever varieties. It applies to the standard and the clip bar levers. However, the objective is not to design all needed fixtures, given the research is considered a toy problem, discussed in Section 1.4. Therefore, we only design fixtures for the range 14"-18", consisting of levers accounting for   % of the annual demand. Furthermore, we aim to minimise the need for reorientation during assembly by determining the workpiece orientation within a fixture. It is an aspect of DFA discussed in subsection 5.4.1.

Table 6.3: Number of fixtures per process step and applicability to standard and clip bar lever varieties.

Process step	Number of fixtures	Inch size range	Process step	Number of fixtures	Inch size range
Press 1 – Bearing shaft	2	12”-18” 19”-24”	Press 5 – Shaft roll	3	12”-13” 14”-18” 19”-24”
Press 2 – Ball bearings	2	12”-18” 19”-24”	Press 6 – Flaring shaft	3	12”-13” 14”-18” 19”-24”
Press 3 – Flaring shaft	2	12”-18” 19”-24”	Press 7 – Bush bearings	3	12”-13” 14”-18” 19”-24”
Press 4 – Bush roll	3	12”-13” 14”-18” 19”-24”	Press 8 – Dowel	3	12”-13” 14”-18” 19”-24”

The absence of disturbing process forces and the orientation of the workpieces in the fixtures yield no need for any clamps to secure the components. The second phase also determines locators that can constrain the components in five of six degrees of freedom. The unconstrained degree of freedom allows performing the process step and eases placing and removing the workpiece. The locators primarily used are location pins, located such that the fixtures become poka-yoke. It means that the employees can only place components in one correct orientation and cannot use a fixture to assemble another lever variety than for which it is designed. The literature review discussed in subsection 5.4.4 that using poka-yoke increases the ease of a task. Hence, it is especially suitable for the sheltered workshop. It satisfies a variable requirement for the process design. The fixtures for presses seven and eight use faces instead of location pins to constrain the components in five of six degrees of freedom and are also poka-yoke.

The third phase designs the fixture body that houses the location pins or faces and has supports to minimise deflection. Also, it has two holes to align the fixture with the two location pins of the tooling. These elements also allow rapid exchange of fixtures, the application of SMED mentioned in subsection 5.4.3. Figure 6.11 shows the fixture for the first process step, where employees press the ball bearing shaft into the lever. It also includes the proposed colour scheme of subsection 6.4.3. Hence, the employees can use this fixture to assemble levers in the range 12”-13” (red) and 14”-18” (blue) and another fixture for levers in the range 19”-24” (yellow). The fixtures for all process steps are in Figure R.1 to Figure R.8 in Appendix R.

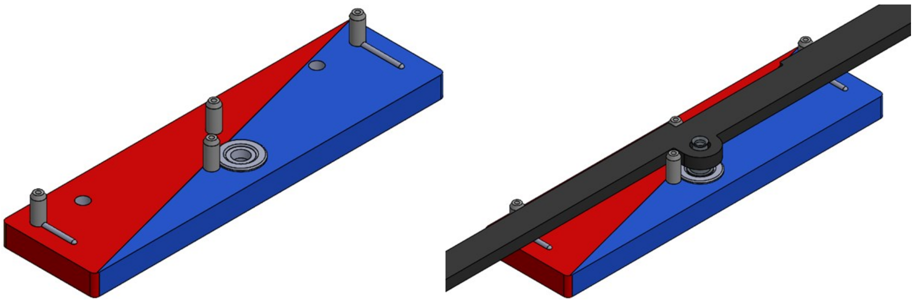


Figure 6.11: Fixture for pressing the shaft for the ball bearings into the levers, lever range 12”-18” with (r) and without the components (l).

The fixtures for the new process design of the lever are poka-yoke, incorporate SMED, eliminate positioning, and eliminate frequent checking before assembly. Thereby, they yield significant savings in changeover and processing times. In addition, the fixtures simplify the process and are less labour-intensive. These aspects help satisfy several of the listed variable requirements of subsection 6.1.2 and the seven design core principles listed in Section 5.5. Examples are simple and intuitive design and visual communication. The simple, intuitive design requires employees with fewer skills than at present. Employees need less training before they can independently assemble levers. They only have to place the components into the fixtures and perform the activity. Hence, the new fixture design improves the flexibility in work schedules and makes introducing new sheltered workshop employees to the process easier.

6.5.2 Pressing tools

The dedicated tooling and some new assembly principles require designing new tools. Only the current tools used for the third and eighth process steps remain suited. Therefore, we develop pressing tools for the remaining six manual presses. With the current manual presses, it is hard to change tools quickly. It does not necessarily mean that all presses suffer from this issue but minimising the number of tool changes is beneficial. Fortunately, we can design for every manual press a pressing tool that is suitable for all component varieties. Thus, switching between different lever varieties only requires changing fixtures. The pressing tools offer the necessary flexibility. Figure 6.12 shows the pressing tool for the second process step, where the employees press the ball bearings onto the shaft. Also, it illustrates the pressing tool in the tooling, the press, and the fixture. All designed pressing tools are in Figure R.9 to Figure R.14 in Appendix R.

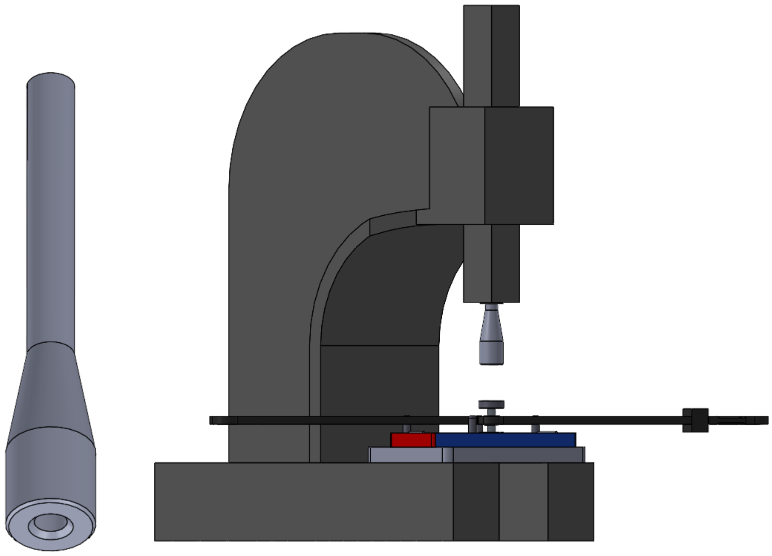


Figure 6.12: Pressing tool for pressing the ball bearings onto the shaft (l) and in the press with the fixture (r).

6.6 Continuous quality improvement

The detailing of the workstations (i.e., dedicated fixtures and tools) decreases the probability of quality issues. However, it has likely not prevented every issue since the current process suffers from quality issues determined in subsection 3.3.1. Furthermore, validity assessment of the quality results in subsection 3.3.5. revealed more issues are occurring than the employees reported. Therefore, we introduce the concept of the Table of Sin (TOS) to reveal every quality issue that the employees encounter. It is a continuous improvement method focused on quality in medium to high-volume processes. Every time the employees encounter a faulty component or reject a product, they place it on the TOS. In a stand-up meeting, a multidisciplinary team can then focus on identifying the root causes of the quality issue. The composition of the team and the time interval differ. A new process generally has a meeting daily with a broad team (e.g., assembly workers, engineers, foremen, manufacturing engineers, purchasers, and quality engineers). Whereas a stable process with few quality issues only has a meeting with the assembly workers, a foreman, and a manufacturing engineer weekly. It is key that these meetings are on the factory floor near the actual process. It creates employee involvement, visualises continuous improvement, and helps understand what actually is happening better. Thus, when the employees encounter a quality issue, they can no longer repair the lever immediately. The root cause of the quality issues is determined first in a TOS meeting. Afterwards, an employee repairs all levers one after the other. The repair hours and replacement components are for this purpose also logged. Hence, it minimises the chance of discrepancies between the ERP and physical inventory, determined in subsection 4.2.2. In addition, the registration of repair hours and replacement components allows quantifying the costs of poor quality: a new KPI to express the severity of the quality issues. Lastly, the overarching objective is to get and keep the TOS empty, and the first day this happens, the team celebrates their victory. Given the current quality issues, the process requires continuous improvement of the quality to become a stable process, and thus a TOS is part of the production process design.

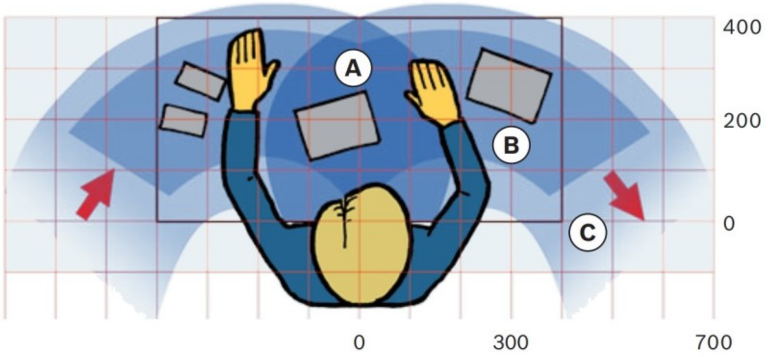
6.7 Ergonomics

An ergonomically designed process yields increased employee motivation and satisfaction, higher performance, greater efficiency, better processing quality, and fewer absences due to illness (Bosch Rexroth, 2012). In addition, it helps realise a design that is equitable in use and requires low physical effort, two core principles listed in Section 5.5. Therefore, we incorporate ergonomics in the workstations, subsection 6.7.1. Subsequently, subsection 6.7.2 introduces a new arrangement of levers in bins to reduce bin weight. Subsection 6.7.3 details the ergonomics of the flow rack. Then, subsection 6.7.4 mentions improvement for the manual pressing. Subsection 6.7.5 discusses the impact of the new process design on repetitive motions.

6.7.1 Workstation

The workstations have to accommodate a wide range of body heights. Hence, it is vital that the working height and reach zones are appropriate. If we adopt the classification system suggested by Bosch Rexroth (2012) to group the employees of the lever assembly, we would assign them to groups two and three: average woman and smallest man (2) and largest woman and average man (3). Based on the average requirements for visual inspection and fine motor skills, the average optimal working height for these groups is 1125 mm for sit-down/stand-up workstations. The height of tables in the process is then the optimal working height minus the workpiece height.

The reach zones also differ per body height group. It means that the tooling, materials, and other equipment have to be easily accessible and arranged in the movement range for the employee. For this purpose, Bosch Rexroth (2012) defined areas A, B, and C, given in Figure 6.13. Area A is the centre of work where the workpiece is situated. It is the optimum area for working both hands and fine motor movements. Area B is for gross motor movements, such as grabbing components with one hand. For occasional handling is area C. In the workstation design of the lever, we place the tooling with the workpiece in area A, the bin flow racks are partially in area A and partially in area B, and area C is vacant. This arrangement minimises torso rotations and shoulder movements, improving the working conditions.



Legend:
- A) Centre of work
- B) Large reach zone
- C) Extended one-hand zone

All dimensions in mm

Figure 6.13: Reach zone for body height group 1: the smallest woman (Bosch Rexroth, 2012).

The work area height should always avoid working above the heart. Otherwise, the blood circulation to the muscles reduces, decreasing the performance. The recommended maximum work area height is 1500 mm (Bosch Rexroth, 2012). Evaluation of all workstations proved that none of the activities requires working above the limit of 1500 mm.

6.7.2 Bin weight

The weight of bins is an important aspect of the working conditions. Currently, employees put 45 finished levers in one bin. The final weight of a bin requires two employees should lift it.

Therefore, smaller bins replace the bins for 45 levers. The bins have supports that can only house 15 levers, reducing the weight to under 12 kilos. Hence, the employees can safely lift a bin without overloading themselves. The number of levers per bin is 15 since a multiple of 15 corresponds to the number of levers in a drum. The levers delivered by the warehouse also use the same principle to reduce bin weight, as visualised in Figure 6.14. The new lever arrangement in the bins guarantees the employees no longer overload themselves if they lift a bin alone.

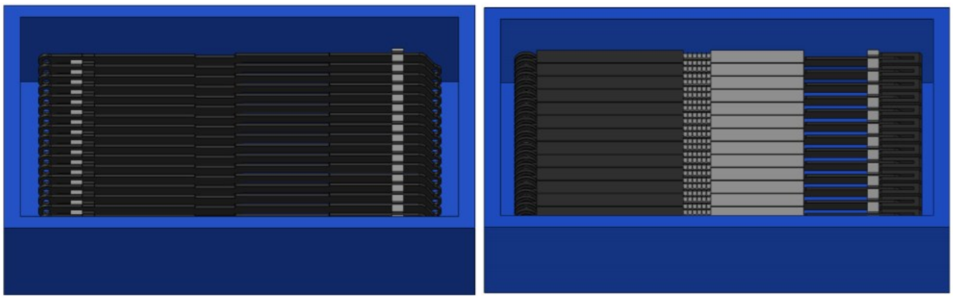


Figure 6.14: New arrangement of the levers (l) and finished levers (r) in the bins.

6.7.3 Flow racks

The weight of bins is also a key aspect of the flow rack design. The location of higher weight bins should be convenient for lifting. For this purpose, Bosch Rexroth (2012) defines three zones for locating bins, illustrated in Figure 6.15. Zone A holds the bins of the highest weight. The bins of lower weight are in zone B, and the bins for occasional handling are in zone C. The design of the flow rack in Figure 6.9 adopts these recommendations. Zone A is the second and third levels of the flow rack, which holds bins filled with levers. The top and bottom levels are in zone B and house mostly slide blocks since a bin filled with slide blocks is lighter than a bin filled with levers. However, we expect only a limited amount of material handling during a shift. One bin pick per hour is an overestimation for the future state. Thus, the flow rack has the heaviest bins in the most favourable locations, even with the expected limited material handling.

Legend:
A) Higher bin weight
B) Lower bin weight
C) Occasional handling

Figure 6.15: Recommended working heights for flow rack design (Bosch Rexroth, 2012).

6.7.4 Manual pressing

The baseline performance concluded that the workload should not cause any health complaints. When questioning the validity of these findings, since the employees experience health complaints, revealed that the way the employees perform assembly activities is the likely cause. During further examination, a physiotherapist observed and talked with the employees. It revealed that the health complaints originate from bad working postures during manual pressing. For instance, some of the employees who have health complaints perform manual pressing sitting, overloading their shoulders and back. Other have a bad working posture during standing manual pressing. Work sampling photos also show these findings. Two examples are given in Figure 6.16 and Figure 6.17. Therefore, the physiotherapist recommended performing manual pressing standing since sitting is not responsible. In addition, training of the employees in what the proper posture is for manual pressing was advised. Documenting this training is wise for future employees. Thus, employees assemble the lever standing in the new production process design. Moreover, they should receive training on how to perform manual pressing properly.

Confidential

Figure 6.16: The working posture of an employee during sitting manual pressing.

Figure 6.17: The working posture of an employee during standing manual pressing.

6.7.5 Repetitive motions

The one-piece flow design of the lever assembly also improves the ergonomics. It removes the repetitiveness of the batch production, where employees perform the same activity 45 times in a row. The new process design provides more variety in work. Furthermore, assembling a lever standing realises dynamic work. The employees perform a process step, walk a short distance, and perform the new process step. This alternation stimulates blood circulation and eliminates the static character of batch production (Bosch Rexroth, 2012). So, the one-piece flow of the lever assembly creates more dynamic versatile work for the employees.

6.8 Scheduling

The new production process design of the lever has the flexibility to changeover relatively quickly. It is responsive to fluctuations in demand and creates flow. These elements offer the opportunity to change the production schedule. The new production schedule levels the lever varieties in volume and type. The new arrangement of levers in the bins levels the volume. In addition, the arrangement and quick fixture changeovers allow mixing lever varieties. Levelling volume and type decrease the lead time, create a process less sensitive to demand fluctuations, and reduce employee stress that can accompany fluctuating workloads (Hamel, 2013).

A Heijunka box can visualise the new production schedule. It assigns POs to certain time slots such that the employees see what needs to be assembled and whether they are on schedule or not (Theisens, 2017). Therefore, the shelf racks incorporate a Heijunka box by adding the working day signs, see Figure 6.9. A bin located in 'today' triggers the employees to start assembly. As mentioned, these bins consist of levers and slide blocks that are not inventory but delivered to demand. The Heijunka box mixes these lower demand lever varieties with the lever varieties in inventory. The employees assemble the higher demand levers in fixed quantities, which levels workload unevenness. The time interval is days since the future performance of the process is yet unknown. However, the time interval set to hours is likely. The implementation plan details in subsection 8.1.1 the Heijunka box since the expected future performance has been determined. So, the production schedule of the lever assembly levels volume and type by using a Heijunka box.

6.9 Future state lever assembly

The final detailing of the production process design into the future state starts with evaluating and selecting one of the layouts in subsection 6.9.1. Then, subsection 6.9.2 discusses the counterclockwise product flow. Afterwards, subsection 6.9.3 visualises and summarises the new production process design of the lever in a future state VSM.

6.9.1 Layout selection

The first layout evaluation excluded the I-shaped and L-shaped layouts based on communication and overview, line balancing, and walking distance. It left the O-shaped and U-shaped layouts as potential layouts. After further detailing of, for example, the material supply and workstations, we can evaluate the two remaining layouts once more. For this purpose, we place both variants in the existing floor area and evaluate them on the criteria integration of material supply, floor area, and safety. Figure 6.18 gives an impression of the lever assembly process when the layout is O-shaped or U-shaped.

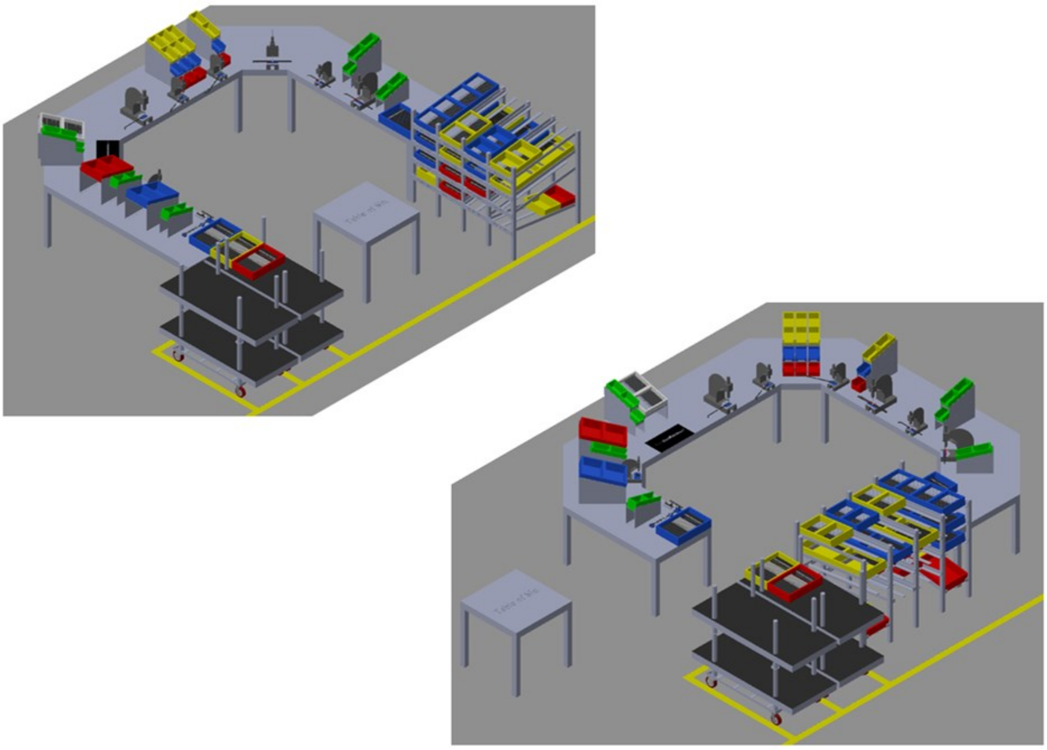


Figure 6.18: Lever assembly process with an O-shaped (r) or U-shaped layout (l).

Material supply integration

The integration of the material supply requires sufficient space around the tables to let the warehouse employees carry out the milk runs. Therefore, the tables do not extend toward the walls. Next to the main corridor are the flow rack and steel pallets. The steel pallets have their required outbound area. However, the U-shaped layout locates them directly next to the final assembly step. Hence, it is more convenient and requires less walking. The flow rack in the O-shaped layout has little room at the back for replenishment. The warehouse employee will likely stand in the main corridor during replenishment. For safety reasons, this is not desirable. The U-shaped layout has sufficient space available at the back of the flow rack. Also, it has room for a deeper flow rack, which is not possible for the O-shaped layout. Thus, with integrated material supply in the production process design, the U-shaped layout is safer, more convenient, and has flexibility for deeper flow racks.

Floor area

The O-shaped and U-shaped layouts require far less floor area than the current layout. The current process covers 105 m^2, whereas the O-shaped and U-shaped variants need 67 m^2 and 60 m^2, respectively. The location of the TOS causes the difference in floor area between the options. Its location in the O-shaped layout is next to instead of in the process. Otherwise, the number of workstations to balance the workload over would decrease by half. The preference is to locate the TOS in the process. The distance to it is shorter, and it has a more central place in the process, which emphasises its functions. The smaller the floor area, the more favourable the layout is. So, based on the required floor area, the U-shaped layout scores better.

Safety

The safety concerns the escape routes for employees. An escape route has to start at any point of a floor section intended for persons (Ministerie van Binnenlandse Zaken en Koninkrijksrelaties, 2011). The U-shaped layout satisfies this regulation. However, the O-shaped layout requires an escape route from the entrance to the main corridor. Furthermore, the escape route is longer than the escape route for the U-shaped layout. The employees would need more time to get to safety in case of an emergency. Therefore, the O-shaped layout is not convenient. It requires additional safety measures to ensure a safe and longer escape route.

Future layout

The second evaluation of the potential layouts justifies selecting the U-shaped layout in the production process design. The material supply integrates better in the U-shaped variant, making it convenient, safer, and more flexible. Furthermore, the TOS has a favourable position, a more central place in the process, which emphasises its functions. In addition, the U-shaped layout covers 60 m^2, about 10% less than the O-shaped variant. Finally, the O-shaped layout requires additional safety measures only to ensure a safe and longer escape route.

6.9.2 Counterclockwise product flow

The flow of the product through the U-shaped assembly cell is counterclockwise. The reason is that all the current employees are right-handed. As they move through the cell, their dominant hand, which they use for fine motor tasks, is closer to the workpiece sooner. After performing an assembly task, the employees do not need fine motor skills to pass the product to the subsequent step. Thus, they use their non-dominant hand to pick the product and have their right hand available for the next fine motor tasks (e.g., pick one component and place it into the fixture). Figure 6.19 is a top view of the process design and gives the counterclockwise flow and the location of every process step (Pereira, 2011).

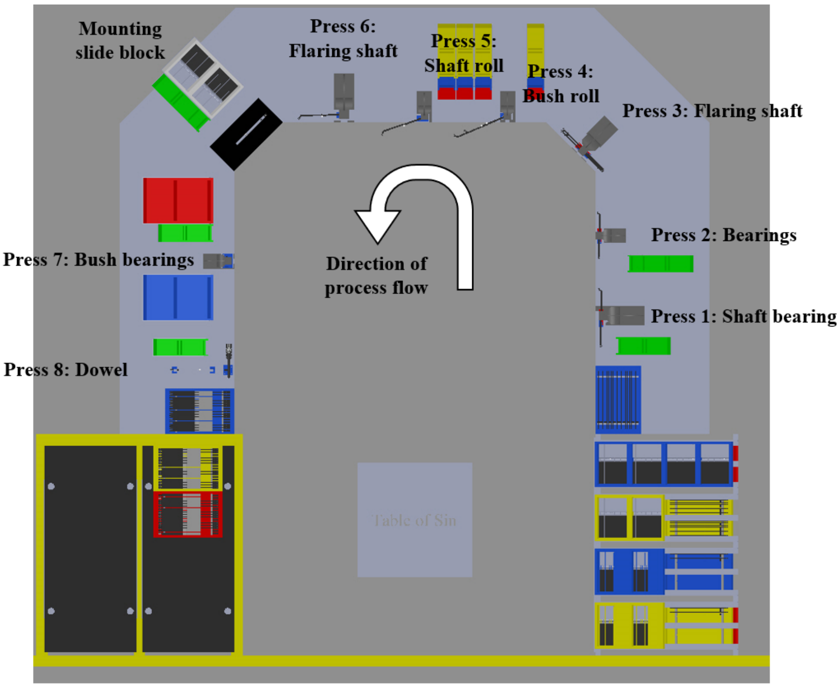


Figure 6.19: Top view of the lever assembly process with the process flow direction and the location of every process step.

6.9.3 Future state VSM

The lever assembly has a new process design: the future state. The new design includes improvements in ergonomics, facility layout, inventory control, material supply, quality improvement, process fundamentals, scheduling, and workstation design. Some of these aspects are part of the VSM. Hence, creating a future state VSM is worthwhile. It visualises and summarises the new production process design of the lever. Figure 6.20 shows the future state VSM of the lever assembly.

The new lever assembly is a one-piece flow process in a U-shaped manufacturing cell. Its assembly sequence changes to pressing bearings, pressing rolls, mounting slide block, pressing bush bearings, and joining lever base to pivot block. The process has a TOS for continuous quality improvement. It collects the rejected components and levers. After root cause analysis, it communicates the required replacement components and hours for rework to the MPS.

The material supply to the process consists of two streams. The warehouse delivers slide blocks and levers with intermittent demand equal to the demand. It supplies the other levers, slide blocks, and all other components using the two-bin principle by using milk runs. The two-bin principle controls the physical inventory, whereas backflush deducts the inventory in the ERP system with every finished pick order in the warehouse. Also, the warehouse collects the finished levers daily. A tugger train transports a steel pallet with bins up to 15 levers each.

The production schedule levels levers in volume and type using a Heijunka box. It makes the lever assembly more responsive to fluctuations in demand and creates flow. The employees log the required assembly hours after finishing a PO for the ERP system.

The future performance of the lever assembly process is yet unknown. Therefore, the cycle, lead, and processing times have, for example, no value. Determining the expected performance of the new production process design is the next research step.

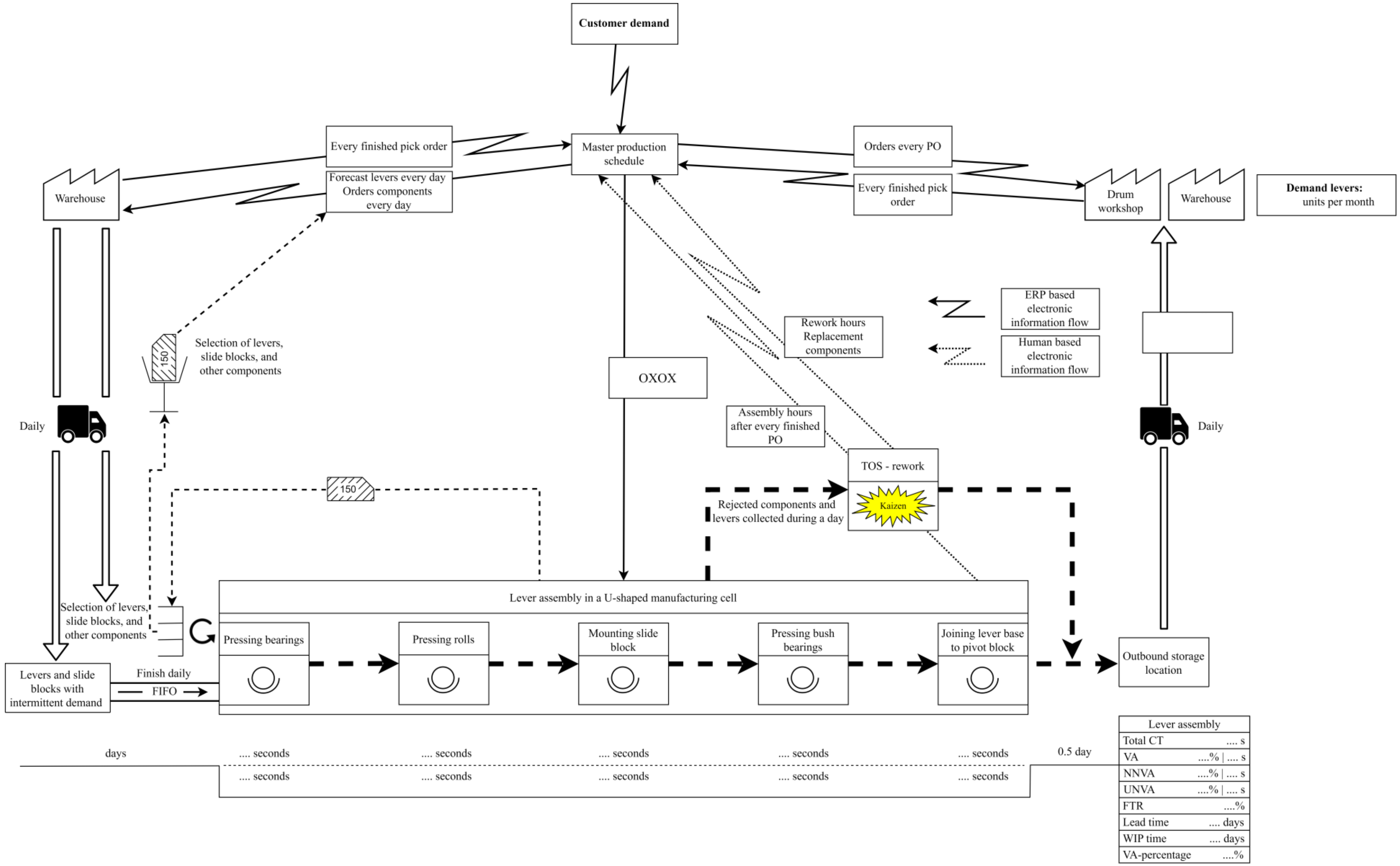


Figure 6.20: Future state VSM of the lever assembly.

6.10 Risk inventory and evaluation process design

The previous section briefly discussed safety in the evaluation of the two remaining layouts. However, with a new process design of lever, other potential safety risks may have emerged. Safety is an important aspect of the process design, and thus we need to ensure that the working conditions for the employees are safe. To inventory and evaluate potential safety risks, we carried out a RI&E. For this purpose, we used the Fine-Kinney method, which lists health and safety risks per work activity and assesses the likelihood of occurrence, duration, and effect of a hazard on the employees. Section S.1 in Appendix S elaborates on the Fine-Kinney method. The RI&E compared the current state with the future state lever assembly process. It specified three main activities material preparation, assembly, and storing of finished products. Subsequently, we listed per main activity potential risks. The evaluation of the risk scores resulted in three subsequent actions. The first is the active monitoring of the ergonomic conditions discussed in more detail in subsection 7.4.5. In addition, the other two actions require design changes by Engineering. They are the slide block and the engineering fit between the bush bearing and the pivot block. Section 8.1 outlines these activities in the implementation plan. The risk scores of all the other potential risks were considered acceptable. Subsection S.2.1 in Appendix S elaborates on the risk identification and evaluation. The QESH department approved the RI&E because the potential risks covered all areas and were realistic. Also, the risk scores were appropriate, and the subsequent actions were logical given their risk scores. Thus, the RI&E of the future state lever assembly is reliable and valid, discussed in more detail in subsection S.2.2 in Appendix S.

6.11 Conclusion

The sixth chapter focused on designing a new production process design for the lever. It first selected a framework to follow in the design process and listed the requirements of VMI. Then, it proceeded with planning the process. Afterwards, an evaluation examined potential process layouts and excluded half of them. Detailing the material supply and inventory control followed. Subsequently, we designed the workstations in more detail and introduced a concept for continuous quality improvement. Thereafter, the working conditions for the employees improved by incorporating ergonomics in the process design. We proceeded with a new scheduling approach for the process design. Afterwards, we finalised the process design of the lever to the future state VSM. Hence, the chapter answered the fifth research question: "*Which design is best suited for the selected production process of production group E720*".

Positioning the volume and variety characteristics of the lever in the product-process matrix gave three combinations of process and layout types. These were a mass process with a cell layout, a mass process with a product layout, and a continuous process with a product layout. The lack of flexibility for product varieties and the perspective for including the earlier excluded truck levers in the process justified excluding the first and last combinations. In the product layout, the material flow follows a line flow since it minimises the material handling, and the process design does not require any backtracking. The pull principle of JIT regulates the material flow. It is the most suitable production control strategy since QRM with POLCA and JIT with CONWIP suit multi-stage processes with high product varieties, which the lever not is.

The lever assembly becomes a one-piece flow process by implementing a new assembly method. It presses the bush bearings into the pivot block instead of glueing them, which replaces three process steps with one. A new assembly method for mounting the lever base to the pivot block should tackle the origin of % of the repairs. These two new assembly methods reduce the assembly time, improve working conditions, and ease the assembly significantly. Moreover, the proposed design change of the slide blocks is financially viable but requires determining technical feasibility. It reduces the assembly time, decreases component costs, and improves working conditions. Also, it requires the assembly sequence in the new process design to be: pressing bearings, pressing rolls, mounting slide block, pressing bush bearings, and lastly joining lever base to the pivot block.

The new process design has new tooling for the new assembly methods and additional tooling to provide every process step with dedicated tooling. Evaluation of the tooling placed in the potential I-shaped, L-shaped, O-shaped, and U-shaped layouts, justified excluding the I-shaped and L-shaped layouts. Their workstation arrangements do not allow effective communication and overview. Also, their line balancing potential is limited, and the walking distances to complete one lever with one employee are far greater than the O-shaped and U-shaped layout.

The material supply in the new process design consists of two streams. The first delivers levers and slide blocks of levers varieties with intermittent demand equal to the demand. The second stream supplies the other levers and slide blocks, which account for % of the demand and % of the orders annually, and the other lever components. The latter stream uses the two-bin Kanban system to control the inventory physically in the process. Backflush deducts inventory in the ERP system with every reported finished pick order of components in the warehouse. Milk runs supply the materials to the process, and tugger trains collect steel pallets with the finished levers daily. A flow rack close to the process stores the levers and slide blocks, and small flow racks hold the other components in the process. A colouring scheme supports the employees in picking the right components. The bin with levers has the leading colour and indicates which components the employees should use.

The fixtures for the new process design are poka-yoke and eliminate positioning errors. Furthermore, they incorporate SMED to provide quick fixture changeovers. The pressing tools in the manual presses suit all component varieties. Hence, switching between different lever varieties only requires changing fixtures. There are fixtures for the levers in the inch ranges 12”-13”, 14”-18”, and 19”-24”.

The TOS facilitates continuous quality improvement in the process design. A multidisciplinary team focuses on root causes analysis of component and quality issues. In addition, the TOS meetings are near the process with the employees to create employee involvement. Moreover, the TOS logs repair hours and replacement components to quantify the costs of poor quality.

The process design incorporates ergonomics in bin weights, flow racks, manual pressing, repetitive motions, and workstations. Smaller bins with fixed lever arrangements reduce bin weight to under 12 kilos. The flow rack has the heaviest bins, under 12 kilos, in the most favourable locations in terms of height. To improve the manual pressing in the new process, the employees perform these activities standing because sitting is not responsible. Furthermore, they receive training on the correct posture for manual pressing. The one-piece flow in the new process design removes the repetitiveness and introduces more variety in activities. Moreover, standing assembly combined with walking creates more dynamic work. The ergonomics in the workstations set the working height to 1125 mm to match employee body heights. It also arranges the tooling and components such that they minimise torso rotations and shoulder movements. Lastly, it ensures that the employees do not perform activities above 1500 mm, which would reduce blood circulation.

The production schedule levels levers in volume and type using a Heijunka box. It makes the lever assembly more responsive to fluctuations in demand and creates flow. It mixes lower demand lever varieties with the lever varieties in inventory. The employees assemble the higher demand levers in fixed quantities, which levels workload unevenness. Bins with the lower, intermittent demand lever varieties in flow rack locations trigger the employees to assemble.

The second layout evaluation excluded the O-shaped layout and selected the U-shaped layout in the production process design. The material supply integrates better in the U-shaped variant, making it convenient, ensuring safety, and more flexible. Furthermore, the TOS has a favourable central position in the process. In addition, the U-shaped layout covers 10% less floor space than the O-shaped variant. Lastly, the escape route in a U-shaped layout is shorter than in an O-shaped layout. The material flow in the U-shaped layout is counterclockwise since all employees are right-handed. Their dominant hand, required for fine motor tasks, is closer to the workpiece sooner.

The risk scores of the RI&E resulted in three subsequent actions. The first is the active monitoring of the ergonomic conditions. The other two actions require design changes by Engineering. They are the slide block and the engineering fit between the bush bearing and the pivot block. The risk scores of all the other potential risks were considered acceptable. The QESH department approved the RI&E because the potential risks covered all areas and were realistic. Also, the risk scores were appropriate, and the subsequent actions were logical given their risk scores. Thus, the RI&E of the future state lever assembly is reliable and valid.

The lever has a new production process design. The next step is to determine the feasibility of the new process design. Therefore, the next chapter addresses the approach for process measurement and presents the expected future performance of the lever assembly process.

7 Future performance

The seventh chapter determines the future performance of the new lever process design. It first introduces the test setup and test approach for the process measurement in Section 7.1. Then, Section 7.2 describes the data collection plan used to determine future performance. Section 7.3 mentions employee training in ergonomics and mastering the new process design. Subsequently, Section 7.4 presents the future performance of the lever assembly process and discusses its reliability and validity. Section 7.5 balances the workload of the assembly process over the employees. Lastly, Section 7.6 finalises the chapter with a conclusion of the main findings.

7.1 Proof of concept

Determination of the feasibility of the new process design and verification of the new assembly methods, presented in subsection 6.2.4, is through a proof of concept. Therefore, a test setup represents the new production process design of the lever. We decided to experiment with a physical model of the system, as Law (2015) classified this way of system experimenting. Experimenting with the actual system requires a substantial financial investment. Furthermore, we excluded a mathematical model since its hard to simulate the complexity and dynamic nature of, for example, ergonomics and human behaviour. Moreover, a mathematical model represents a system of logical and quantitative relationships Law (2015). Defining these relationships generally requires input data of the actual system. This input data lacks and is quite hard to generate without a physical system or system model.

In the proof of concept, we evaluate the scenario where the employees assemble the lever variant 14"-18"-L495. It is a standard lever that accounts for % of the annual demand. The employees assemble only one lever variant because we consider the research a toy problem, discussed in Section 1.4. If the proof of concept demonstrates the feasibility and working principles for this variant, the results for all the standard levers should be similar. These standard levers account for % of the annual production quantity. Also, the clip bar levers follow the same assembly sequence but have one subsequent assembly step, as listed in 6.2.4.

The test setup consists of standard workbenches arranged in a U-shape, given in Figure 7.1 and Figure 7.2. On them are the tooling with prototype fixtures and tools. It is important to note that the prototypes are plastic (fixtures) or mild steel (tools). Thus, the expected lifespan of these prototypes is limited. For daily use, they require industrial-grade equivalents, discussed in more detail in subsection 8.1.1. Furthermore, the assembly is a one-piece flow process. Aspects of the material supply in the test setup are the transport carriers and the two-bin flow racks, including the colour scheme. Backflush and milk runs are not part of the test setup since VMI already uses both principles satisfactorily in the drum workshop. Furthermore, the test setup has a TOS for rejected levers and components, given in the bottom left of the second photo in Figure 7.2. It also includes the ergonomics aspects of bin weight under 12 kilograms, work height of 1125 mm, reach zones, and work area height under 1500 mm.

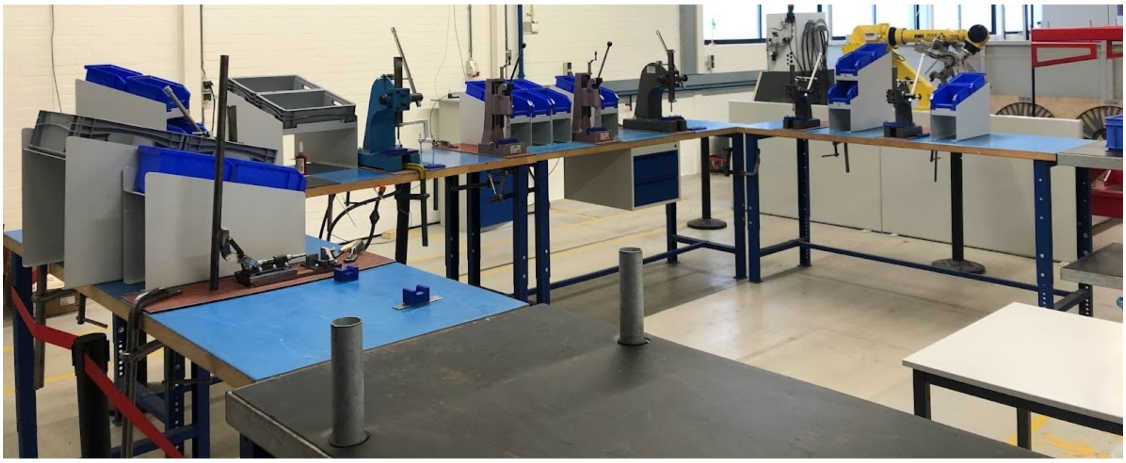


Figure 7.1: Test setup of the lever assembly, seen from the left-hand side.

Figure 7.2: Test setup of the lever assembly, seen from the right-hand side.

7.2 Data collection plan

The data collection plan for the baseline performance defined seven KPIs for process measurement. They related to the CTQs quality, lead time, costs, and ergonomics, listed in Table 7.1. The process measurement uses these seven KPIs once more to compare the baseline performance with the future performance. However, the baseline performance had some issues with reliability and validity. The data collected for the quality and costs KPIs were not entirely reliable and valid, discussed in subsection 3.3.5. Hence, we address solutions to solve these issues. The data collection plan discusses, per CTQ, the measurement method, frequency, and, when applicable, solutions for unreliable and invalid data. It starts in subsection 7.2.1 with the KPIs of quality. Then, subsection 7.2.2 discusses the CTQ lead time. Subsection 7.2.3 elaborates on the costs. Subsequently, subsection 7.2.4 mentions the ergonomics CTQ.

Table 7.1: KPIs used per CTQ to determine the baseline performance.

CTQ	KPI	CTQ	KPI
Quality	Alignment of parts	Costs	Cycle time per PO
	Assembled according to instructions		
Lead time	Value-adding time	Ergonomics	Ergonomics score
	Necessary non-value-adding time		
	Unnecessary non-value-adding time		

7.2.1 Quality

The baseline performance of quality was not completely reliable and valid due to unreported quality issues and employee inaccuracy to the known standard. The latter meant that non-conforming products likely passed inspection. So, the number of quality issues was probably higher than the reported, as discussed in subsection 3.3.5. The following two paragraphs discuss how we can obtain reliable and valid data for both quality KPIs of quality. It starts with the first KPI, alignment of parts, and continues with assembled according to instructions, the second KPI.

Alignment of parts

The alignment of parts refers to bush bearings in the pivot block. Currently, employees use a go or no-go gauge to check if the bearings align correctly and if the friction is not too high. The new assembly method presses the bush bearings into the pivot block and no longer fixates the components with adhesive, presented in subsection 6.2.4.

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can resolve the first issue and relates to component quality and hence is out of scope. Subsection 8.1.1 outlines the procedure to follow to solve this issue. The consequence is if the KPI is part of the performance measurement, the results, and conclusions based thereon are unreliable. So, excluding the KPI alignment of parts from the performance measurement is logical. However, the assembly method remains part of the proof of concept. In case the issue occurs, we record the lever involved and the impact it has. Subsection 7.2.3 describes the exact procedure for these situations.

Assembled according to instructions

Assembled according to instructions are the intermediate and final checks of a lever. The employees currently struggle with whether they pass or reject a lever revealed in subsection 3.2.2. Resolving the is not possible. They are part of the product design and thus out of scope. Fortunately, the new process design includes new fixtures, tools, and tooling. They support the employees better during assembly. For example, the employees can only place components in one only way into the fixture, and the fixture aligns the components with the pressing tool instantly. Hence, the process design should cause less questionable process quality. The other issue with the validity and reliability was unreported repairs while we did observe them. The TOS and absence of repair tools in the proof of concept prevent the employees from performing repairs. Hence, the employees can only place the faulty component or rejected lever on the TOS when they encounter them. It makes the TOS the check sheet for the performance measurement. After the performance measurement, a TOS meeting determines the origin of the quality issues. The origin is either component or process quality. Furthermore, the TOS meeting determines the assembly step where the issue occurred.

The two-sample % defective test in Minitab determines whether the percentage of defective items significantly differs for the two samples. It assumes that the number of defective items in each independent sample is a value of a binomial random variable. The test uses Fisher's exact test to calculate the hypothesis test result and the normal approximation of the binomial distribution to determine the confidence interval. It is important to note that each sample must have at least five defective and five non-defective products to consider the approximation accurate (Minitab, 2017). Determination of the sample size is part of subsection 7.2.3. The objective is to determine whether the defective rate of the baseline performance is significantly greater than the defective rate of the future performance. For this purpose, the hypothesis test uses the number of repairs. It does not distinguish between component and process quality because component quality has very likely caused repairs in the first process measurement. In the baseline performance, all reported quality issues resulted in a repair, discussed in subsection 3.3.1. Hence, the repairs on assembled levers are the defective rate of the baseline performance. A test result lower than the significance level means a significant difference. The significance level (alpha) is 0.05, a typical value in hypothesis testing. Thus, we formulate the following hypotheses:

$H_0: p_1 = p_2$ (the defective rates are equal between samples)

$H_1: p_1 > p_2$ (the current state sample has a greater defective rate than the future state sample)

7.2.2 Lead time

A work sampling study determined the VA, NNVA, and UNVA times in the baseline performance. The results were accurate and valid due to the high number of observations spread over four weeks. Hence, it is logical to use work sampling again for the performance measurement. However, we slightly adapt the work sampling procedure, as mentioned in subsection 3.1.2. The proof of concept focuses on demonstrating the feasibility and working principles. Hence, we do not require such accurate results as the baseline performance. Thus, the employees will assemble a limited number of levers to demonstrate feasibility. We determine the number of levers, which is the sample size, in subsection 7.2.3. It means that the work sampling study concerns a shorter period than the four weeks of the baseline performance. Therefore, we exclude the preliminary sample and do not randomly schedule the observations, as we consider every photo an observation.

7.2.3 Costs

The costs to assemble a standard or clip bar lever were not reliable and valid in the baseline performance. The data had high numbers of unrealistic outliers resulting in a standard deviation almost equal to the mean. Thus, we have to obtain new cycle times to calculate the assembly costs. For this purpose, we performed a Monte Carlo simulation with input data of 30 processing times per assembly step of the baseline performance. We determined these processing times using the photos of the work sampling study. These variables follow a uniform distribution, and the Monte Carlo simulation performed ten thousand iterations. The simulation resulted in a mean of minutes, a standard deviation of minutes, and a median of minutes. The results substitute the baseline performance as, for example, the mean only slightly deviates from the input data (minutes) and ERP data (minutes). Section V.1 in Appendix V elaborates on the Monte Carlo simulation and its results.

A non-parametric test determines whether the cycle time in the new process design significantly differs from the current situation. The use of a non-parametric test is since no probability distribution fits the results of the Monte Carlo simulation, given in Figure V.2 in Appendix V. Furthermore, we first reviewed the applicability of non-parametric tests before considering a data transformation. The main reasons were that transformed data is hard to interpret or compare, and data transformation is not a condition to perform hypothesis testing. Subsection V.2.1 of Appendix V discusses the reasons in more detail. The evaluation between the two suitable non-parametric tests resulted in selecting the one-sample Wilcoxon test. It is slightly more powerful and more power-efficient. The latter means that it requires a smaller sample size to obtain the same result, mentioned in subsection V.2.2 of Appendix V.

To determine the sample size for the hypothesis test, we first estimated that the future cycle time of the process reduces by %. For this purpose, we estimated the expected percentage the employees spent on every activity category in the future state. The last two assembly steps, pressing the bush bearings and joining the lever base to the pivot block, are new assembly methods. For these two, we estimate the processing time based on five assembly trials adjusted by a factor to incorporate non-assembly-related activities. Lastly, we include additional time to the processing times for every assembly step to compensate for the component and process quality, learning curves, and the plastic fixtures. Afterwards, we determined the minimum sample size (i) and evaluated the standard error, confidence interval of the standard error (ii), and power values (iii). It resulted in a sample size of 100. This sample size is sufficiently large to conclude with a 95% confidence level and 95% power, a cycle time reduction between the current and future state of already %. The determination of the minimum sample size and evaluation of the standard error, confidence interval of the standard error, and the power values are discussed in more detail in subsection V.2.3 to subsection V.2.5 in Appendix V. Thus, we proved that a non-parametric test is applicable and we do not need a data transformation. Hence, the objective is to determine whether the median of the baseline performance is significantly greater than the median of the future performance. For this purpose, we use the median of the Monte-Carlo simulation (minutes) as the null hypothesis median. Furthermore, we use a significance level of 0.05, a typical value in hypothesis testing. A test result lower than the significance level means a significant difference. Thus, we formulate the following hypotheses:

$H_0: \eta_1 = \eta_2$ (the medians are equal between samples)

$H_1: \eta_1 > \eta_2$ (the current state sample has a greater median than the future state sample)

The assembly of the 100 levers is in five assembly sessions of 20 levers, one session per day. We schedule these assembly sessions at different parts of the day. The schedule has, for example, Monday a start time of 9:45 and Tuesday the start time is 13:00. The reason is to improve the validity since it includes randomness and variability in, for example, employee concentration and exhaustion. In addition, two employees alternate in the assembly sessions. These two employees contributed the most to the baseline performance, and the employee with the largest share assembles levers in three sessions. We wanted to include more employees, but with the COVID-19 measures in place at the time, that was not desirable. We use a direct time study to determine the 100 cycle times of levers. For this purpose, we log the start and finish times of every process step. The sum of these nine steps is one cycle time. To do so, a macro in an Excel spreadsheet logs the timestamp every time we call it. We perform the direct time study at a relatively short distance from the employees to minimise employee discomfort and prevent the unintentional influence of the results.

The final aspect to discuss is the processing times of the fourth assembly step, given the exclusion of the KPI alignment of parts, discussed in subsection 7.2.1. , we mentioned that the assembly step remains part of the proof of concept. In case the issue with the occurs, we log the relevant lever. In addition, we then log two processing times. The first one represents the processing time without any issues. It is the time employees would need to press a bush bearing on both sides of the pivot block. The second processing time is the additional time to redo the assembly of one or two bush bearing(s). We use the latter processing time for the cycle time of the lever and hence hypothesis testing. The processing times without any issues are useful for the future when issue. We will use these processing times for workload balancing, elaborated in Section 7.5.

7.2.4 Ergonomics

We applied the ergonomic checklists of TNO and SDU/VHP to evaluate the different aspects of the physical workload for the baseline performance. Recall that these checklists do not require any prior knowledge of risk factors or physical workload. The results were reliable as both checklists independently determined that the ergonomic conditions should be good. However, the results were not viable because they did not take into account the individual way of working. Subsection 6.7.4 discussed that the likely cause of the health complaints is the poor working postures during manual pressing. Therefore, a physiotherapist advised performing manual pressing standing and training on proper posture for assembly. The latter is part of the training week, explained in more detail in subsection 7.3.2. We included standing working and other ergonomics considerations in the new process design of the lever. Hence, the validity of the results of the checklists should be better. Given the reliability and improved validity, we apply both ergonomic checklists again to assess various aspects of physical workload.

7.3 Measurement preparation

The new process design of the lever assembly differs significantly from the current design. The employees require some training and experience to master the new process design. Otherwise, the results of the proof of concept are not representative of actual future performance. Therefore, before the process measurement, the employee had a training week. Aspects of the training week were assembly training discussed in subsection 7.3.1. Furthermore, the employees had ergonomic training mentioned in subsection 7.3.2. The assembly training provided the possibility to make minor changes to the process design based on employee suggestions. Subsection 7.3.3 elaborates on the process improvements. Lastly, subsection 7.3.4 describes the script we created in case of an incident during the process measurement.

7.3.1 Assembly training

The new process design of the lever assembly includes numerous changes such as two new assembly methods, one-piece flow, and poka-yoke fixtures. It requires the employees to learn and habituate to the new process, especially since they are sheltered workshop employees. Therefore, the employees had a training week with training sessions in which they assembled a few levers. Humans learn and remember by repetition. Otherwise, they lose the information over time. The forgetting curve is a visual representation of how humans forget different pieces of information over time when they do not attempt to retain them (Educationcorner, n.d.). Figure 7.3 presents the forgetting curve. The employees had a training session on Tuesday, Wednesday, and Friday in the training week. The start of process measurement was planned on day six of the curve: a Monday. The better the employees are used to the new process design, the more representative the results are as future performance. The training session thus had two functions, initiate the learning curve and retain the newly learned information to improve the reliability and validity of the process measurement. Figure 7.4 gives an impression of the assembly training with the employees.

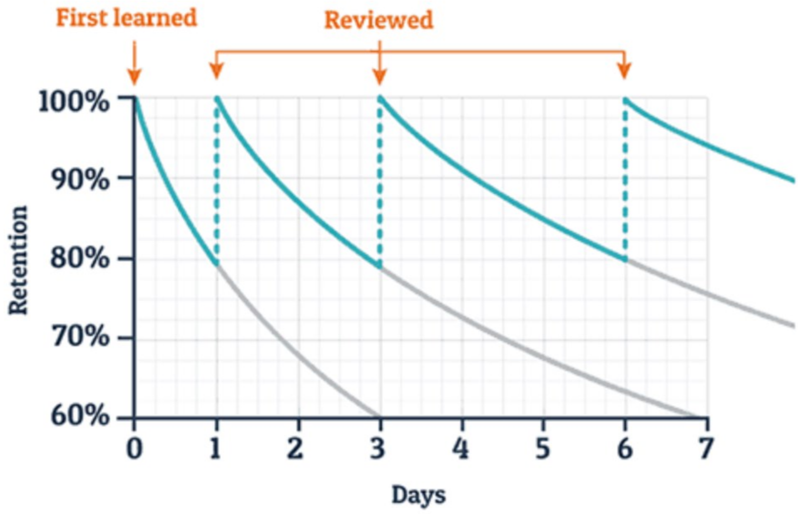

Figure 7.3: Information retention of humans over the days (Educationcorner, n.d.).

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Figure 7.4: Impression of the assembly training for the employees.

7.3.2 Ergonomic training

Observation of the employees by a physiotherapist and work sampling photos revealed bad working postures of the employees during manual pressing. The new process design includes performing the assembly standing, discussed in subsection 6.7.4. In addition, it suggested training the employees in what the proper posture is for manual pressing. The suggestion became a part of the training week. A physiotherapist demonstrated several working postures for manual pressing in the first training session. These postures include the position of the legs and shoulders, reaching for the press handle, and keeping a straight back. Furthermore, the physiotherapist demonstrated balancing pressing force and manual pressing with one and two arms. Afterwards, the employees started assembling levers, and the physiotherapist coached them during the assembly. The training should help the employees to adopt a better posture during the manual pressing. However, a proper working posture is not changed immediately. It requires repetition and coaching. Therefore, documentation and repetition of the training are essential. We discuss this aspect of the implementation in more detail in subsection 8.1.3.

7.3.3 Continuous process improvement

The training week offered the opportunity to improve the process design further. The employees suggested some alternatives to improve the ease of assembly. Illustrations of these suggestions were drawn on a whiteboard and placed near the test setup, shown in Figure 7.5. For example suggestion one, the employees initially used a small piece of sheet steel to press the bush bearings into the pivot block. The steel sheet was only two millimetres thick. However, it was not convenient. It was too thick for comfortable use in the assembly step. Fortunately, one of the employees suggested using a putty knife. The handle of the putty knife makes it easy to use, and the thickness of the sheet is only 0.5 millimetres. It is an example of a small change that has a major impact on the ease of assembly. Furthermore, it involves the employees in the new process design. After implementing the putty knife, the employees proposed the three additional ideas illustrated in Figure 7.5. It demonstrates employee involvement can greatly improve the process, even if it is only a minor detail. The suggestions that require additional examination or could not be implemented in such a short time are recommendations for further process improvement. These two suggestions are WIP. So, the employee suggestions improve the process design and showcase employee involvement.

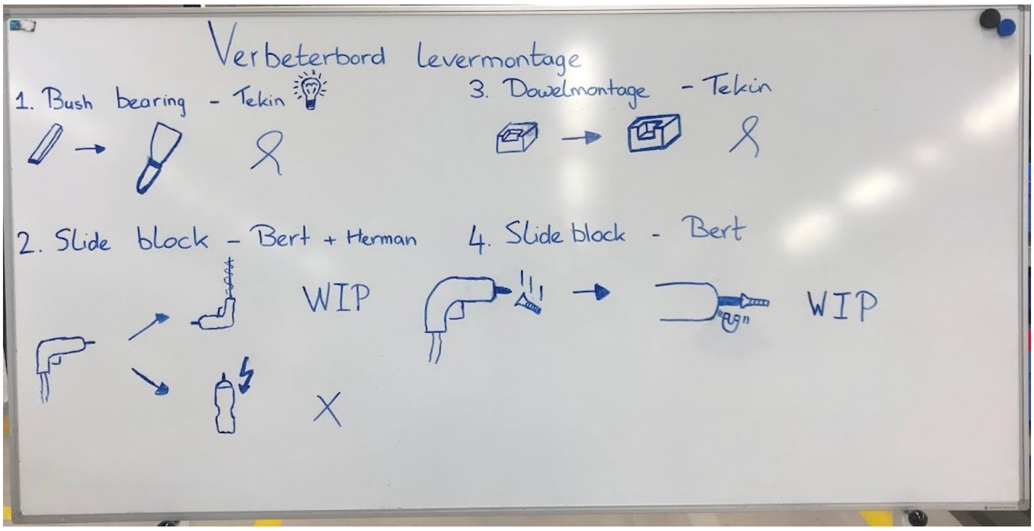

Figure 7.5: Continuous improvement board of the lever assembly with four employee process improvement suggestions.

7.3.4 Process measurement script

The final aspect of the measurement preparation was the creation of a process measurement script. The script lists subjects (e.g., fixture and pressing tool) and potential incidents (e.g., damaged and damaged beyond repair) per subject that can occur. Based on these incidents, we formulated subsequent actions (e.g., pause and stop process measurement) we would carry out when the incident occurs during process measurement. Appendix U lists the entire process measurement script.

7.4 Future performance lever assembly

We discuss the expected performance of the lever assembly per CTQ. First, subsection 7.4.1 mentions the quality aspects and the outcome of the two-sample % defective test. Subsection 7.4.2 presents the performance of the lead time KPIs. Afterwards, subsection 7.4.3 gives the expected assembly costs of a lever and determines whether the cycle times have decreased significantly. Subsection 7.4.4 presents the results of the ergonomic study. Then, subsection 7.4.5 discusses the validity of baseline performance.

7.4.1 Quality

At the end of the proof of concept, quality issues were on the TOS, of which related to process quality and to component quality, as Figure W.1 in Appendix W shows.

. Therefore, we list some key activities in the implementation plan to improve (component) quality in Section 8.1. The policy we adopted ensured 20 approved levers per assembly session to assure 100 cycle times for the one-sample Wilcoxon test. Hence, the employees assembled levers in total. Figure 7.6 gives the number of component and process quality issues per assembly step over the days. It reveals that % of the quality issues, all component quality, originate from the assembly step where the employees press the rolls. Also, it shows the employees encountered no quality issues in the assembly steps that mount the slide block and join the lever base to the pivot block. A very interesting finding, especially since the latter assembly step accounted for % of the repairs in the baseline performance. The prototype of the new assembly step has demonstrated its working principle, and it has potential for further development. The assembly method for pressing the bush bearings into the pivot block also demonstrated that it works as envisioned and has potential for further development.

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Figure 7.6: Number of quality issues divided into component and process quality per assembly per day.

We express the quality in the first time right (FTR) percentage. For this purpose, we determined the number of repairs. This policy is similar to the baseline performance, where all reported quality issues resulted in a repair. Thus, we could not distinguish between component and process quality because component quality has likely caused repairs in the first process measurement. The number of repairs was because we added the partly assembled levers with component quality issues to the four items with process quality issues. The repairs resulted in a lever assembly FTR percentage of %, which is % greater than the FTR percentage of the baseline performance. Figure 7.7 visualises the improvement in the FTR percentage of the lever assembly. If we express this in other words, the employees would have performed one repair in levers, which currently is one repair in levers. Hence, the number of repairs has more than halved. The FTR percentages per assembly step are in Figure W.2 to Figure W.6 in Appendix W. They show both minor improvements and minor deteriorations in percentages. The main reason is that the sample of compared to the of the baseline performance is relatively small. Hence, one or two repairs have quite an impact on the FTR percentages. However, the greatest improvement is still the new assembly method for joining the lever base to the pivot block. It eliminated % of the quality issues of the baseline performance. Its FTR percentage increased by % to %. The employees performed zero repairs, an unprecedented result.

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Figure 7.7: FTR-% of the lever assembly overall in the current and future state.

We examined whether the percentage of defective items significantly differs using the two-sample % defective test. We performed a one-sided test where we assumed as the alternative hypothesis that the future performance has a lower defective rate than the baseline performance. The test yielded a p-value of 0.021, given in Figure W.7 of Appendix W. The p-value is lower than the 0.05 significance level. Hence, the percentage of defective items in the baseline performance is significantly greater than in the future performance. The power of the test is just over 0.7. If we had failed to reject the null hypothesis, we would have a probability of 0.7 that this conclusion was false. However, since the p-value is not significant, the power of the test is irrelevant. So, the new process design of the lever has significantly improved the quality.

7.4.2 Lead time

The VA percentage in the future state of the lever assembly increased by % to over %, presented in Figure 7.8. Simultaneously, the time spent by employees on NNVA and UNVA activities decreased by % to % and % to %, respectively. It means the new process design of the lever allows the employees to meet the specified % VA percentage. Of the nine activity categories shown in Figure 7.9, the category repair has the greatest decline. The reduction of % is understandable due to significant improvement in the quality aspects. Moreover, the new organisation of the material supply with, for example, the two-bin system placed in the process causes a decrease in material handling. Furthermore, the categories setup and clean up are around %. They indicate the employees spent far less time on secondary activities due to the new workstation design. In addition, the policy of 20 approved levers per session includes an indication of the expected time required to assemble replacement levers. Important to note the new process design also impacts the categories study and away. However, using a proof of concept can underexpose these categories. Therefore, we assess the validity critically in subsection 7.4.5. In short, the future state of the lever assembly has a % VA percentage, % NNVA percentage, and % UNVA percentage.

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Figure 7.8: VA, necessary NVA, and unnecessary NVA percentages in the current and future state lever assembly process.

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Figure 7.9: Time distribution per activity category in the current state and future state lever assembly process.

7.4.3 Costs

We distinguish between the cycle time and effective cycle time in assembly costs calculation. The reason is the transition from a batch process to a one-piece flow process. Personal time (e.g., fetching a cup of coffee or visiting the bathroom) was part of the cycle time of a batch. However, with a one-piece flow process, the employees finish the assembly of one lever before taking some personal time. Hence, we define the effective cycle time as the end time minus the start time of the assembly session divided by 20. The average of the five assembly sessions is the effective cycle time of the lever assembly process. The current cycle time includes the time needed for ultrasonic cleaning per product (minutes), determined in subsection 4.2.3, and is minutes. The effective cycle time of the lever in the future state is minutes, presented in Figure 7.10. It is a massive reduction of almost %, % more than we initially estimated. It proves that the new process design of the lever has an enormous improvement potential.

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Figure 7.10: Effective cycle time of the levers in the current and future state.

The cycle time is the sum of the processing times per assembly step. Figure 7.11 shows the processing times per assembly step in the current and future state lever assembly process. It reveals that every assembly step has a minimum reduction in the processing time of almost %. Furthermore, the final two assembly steps have an even higher decrease in processing time by over %. The main reasons are the elimination of process steps and the reduction in workload for pressing the bush bearings. The elimination of quality issues and the new assembly method are the main reasons for joining the lever base to the pivot block. The sum of the five processing times equals minutes. It means that the effective cycle time includes seconds per lever for non-assembly-related activities.

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Figure 7.11: Processing times per assembly step in the current and future state lever assembly process.

We examined whether the cycle time median of the current and future states differ significantly. For this purpose, we performed a one-sided one-sample Wilcoxon test. We assumed as the alternative hypothesis that the median cycle time of the future performance is lower than the cycle time of the baseline performance. We used a 95% confidence level and defined the null hypothesis median as seconds (minutes). The test yielded a p-value of 0.00, depicted in Figure W.8 in Appendix W. The value is lower than the 0.05 significance level. Thus, the median of the baseline performance is significantly larger than the median of the future performance. Given the enormous reduction in cycle time, a p-value of 0 is not an unexpected outcome. The power of the test is 1, given in Figure W.9 in Appendix W. If we had failed to reject the null hypothesis, we would have a probability of 1 that this conclusion was false. However, since the p-value is not significant, the power of the test is again irrelevant. So, the new process design of the lever has significantly reduced the cycle time of the levers.

The before/after I-MR chart in Figure 7.12 visualises the difference between the current and future state of the lever assembly process. It shows that the upper and lower control limits of the individual values have been reduced enormously. Hence, the mean of the future state is significantly lower. Also, the standard deviation was reduced by %, resulting in the standard deviation of the future state process being significantly lower. The moving range chart also visualises the massive decline in the spread of cycle times between the current and future states.

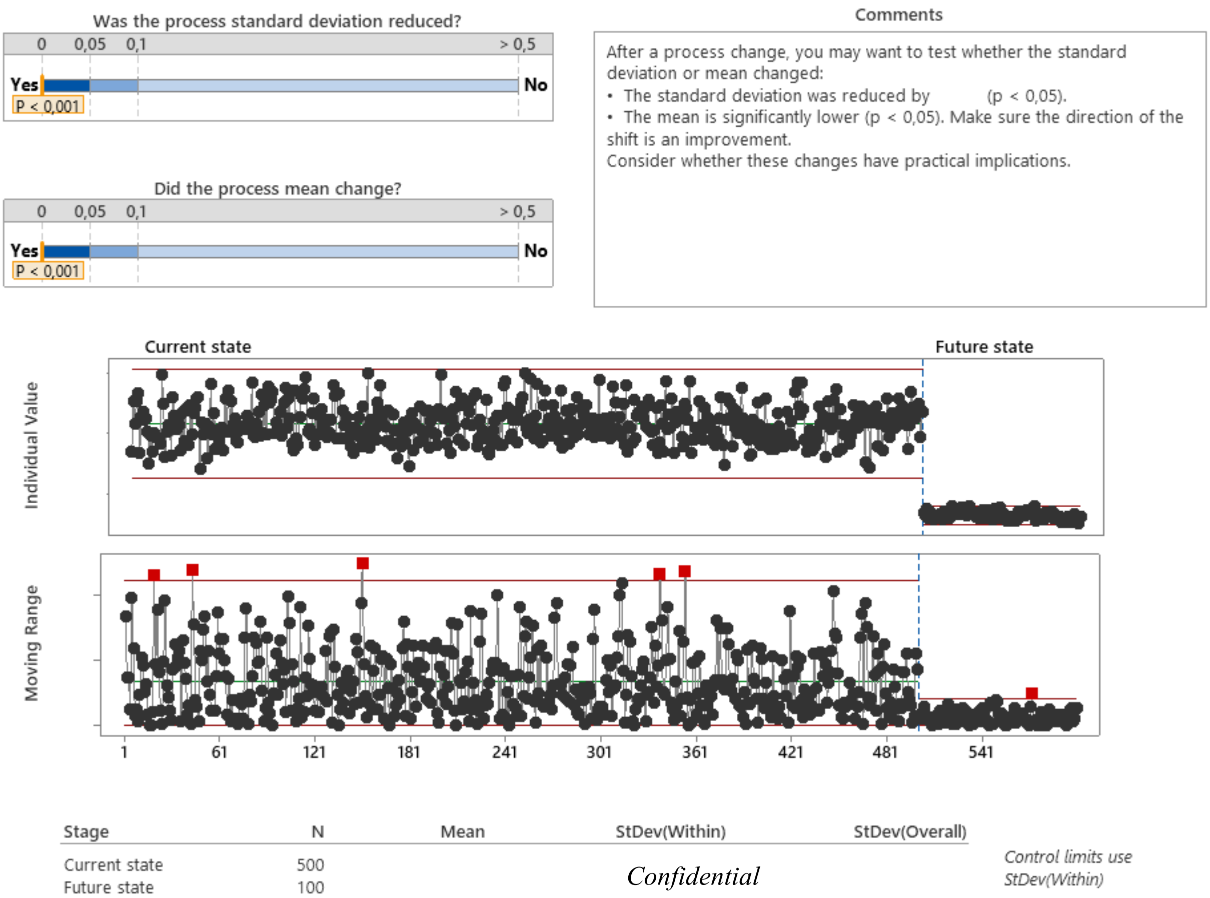

Figure 7.12: Before/after I-MR chart of the current and future state lever assembly process.

In the proof of concept, the employees assembled the lever variant 14"-18"-L495, a standard lever that accounts for % of the annual demand. Recall from Section 7.1 that if we demonstrate the feasibility and working principles for this lever variety, all standards levers should yield similar results. As mentioned, the standard levers account for % of the annual demand. The assembly costs for a standard lever with a cycle time of minutes are € in the current state. In the future state, the effective cycle time becomes minutes, and the assembly costs for a standard lever are € . A saving of € per lever makes the process design most likely to be financially viable. The cost-benefit analysis discusses the financial viability in more detail in Section 8.2. As the standard levers account for % of the annual production quantity, the remaining % are clip bar levers. We cannot calculate the assembly costs of these levers exactly since the employees did not assemble any in the new process design. However, the mechanical and the vacuum clip bar levers follow the same assembly sequence as the standard levers but have one subsequent step. Hence, we can deduct the same savings per lever from the clip bar levers. As an indication, the assembly costs for mechanical and vacuum clip bar levers are € and € in the future state, respectively. Thus, the assembly costs for a standard lever are € in the process design of the lever assembly process. The expected assembly costs for a mechanical and vacuum clip bar lever are € and € , respectively.

7.4.4 Ergonomics

The two ergonomic checklists are comprehensive questionnaires on a range of aspects, and they do not require any prior knowledge of risk factors or physical workload. The approach was to base the answers on the best possible expected working conditions. The main reason for this is that the employees only assembled 100 levers in a short amount of time. Hence, it is harder to, for example, determine how many minutes per hour the employees will have their arms in a non-neutral posture.

The TNO checklist uses a three-colour traffic light to score the risk assessment per aspect. It gives the lever assembly in the future state on all aspects a green score, listed in Table 7.2. Therefore, the TNO checklist states there is no need to perform a detailed assessment or fill out another assessment form. A similar result as in the baseline performance and no quantification of any improvements or deteriorations. Fortunately, the Fysisnel checklist uses risk assessment scores per aspect ranging from one, abominable, to ten, excellent. Table 7.3 presents the scores of the lever assembly in the current and future state using the Fysisnel checklist. It scores the future state lever assembly on all aspects a seven or higher. Hence, the checklist states there is no need to undertake action. The categories of lifting and repetitive motions have improved. Lifting increased due to decreasing the bin weight to under 15 kilograms. The more dynamic one-piece flow standing assembly process improved the repetitive motions since employees no longer perform 45 times the same activity. Unfortunately, we also see a deterioration of the working postures by one. It is the result of the higher output rate. The more employees perform certain activities per hour, the more frequently they have a bad working posture. Given we cannot exactly determine some aspects of these checklists, active monitoring of the ergonomics conditions is vital. So, the ergonomic conditions in the new process design of the lever should be good, but active monitoring is recommended.

Table 7.2: Risk assessment scores of the lever assembly per aspect in the future state using the TNO checklist.

Activity	Risk assessment score	Activity	Risk assessment score
Lifting and carrying	Green	Hand-arm vibration	Green
Pushing and pulling	Green	Whole body vibration	Green
Hand-arm tasks	Green	Energetic overload	Green
Working postures	Green	Energetic underload	Green
Computer-related work	Green	Existence of task-related complaints	Green

Table 7.3: Risk assessment scores of the lever assembly per aspect in the current and future state using Fysisnel.

Activity	Lifting	Carrying	Pushing & pulling	Vibrations	Working postures	Repetitive motions	Energetic load
Current state	9	10	8	10	8	8	10
Future state	10	10	8	10	7	9	10

To summarise the future performance, we return the values to the CTQ tree. Figure 7.13 presents the current and future performance of the lever assembly process.

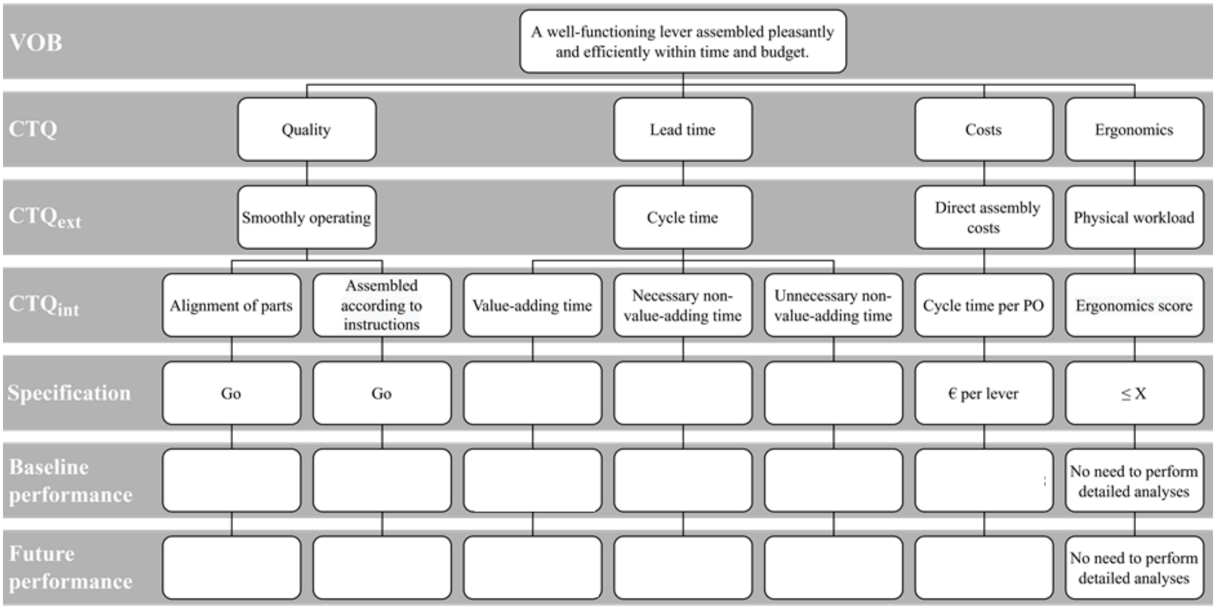

Figure 7.13: Overview of current and future performance of the lever assembly process.

7.4.5 Validity

The baseline performance had some issues with the reliability and validity of the results. The data collection plan for determining future performance included several solutions to overcome these issues. Assessment of the future performance can only determine whether these solutions resulted in reliable and valid data. Therefore the following paragraphs discuss the reliability and validity of the results.

Quality

The number of quality issues on the TOS was at the end of the proof of concept. of these issues required repair since we counted the number of repairs similar to the baseline performance. The number of repairs is reliable because the absence of repair tools in the proof of concept prevented the employees from repairing a rejected lever. Furthermore, observing the employees did not reveal any other product repair. The outcomes of the attribute agreement analysis in Section 3.2 revealed that the employees assessed conforming levers as non-conforming and vice versa. Assessment of the rejected levers proved they were indeed in need of repair. Hence, we can rule out conforming levers assessed as non-conforming. Exclusion of non-conforming levers assessed as conforming by the employees is more difficult. We did not review the 100 approved levers. However, the new process design with the fixtures, tools, and tooling results in less questionable quality. For instance, the fixtures allow assembly in only one way, and it aligns the components instantly with the pressing tool. The new process design has reduced the probability of a defective lever. Hence, it is unlikely that the employees assessed a non-conforming lever as conforming. The number of repairs is thus reliable and valid.

The two-sample % defective test determined that the defective rate of the baseline performance is significantly greater than the defective rate of the future performance. We adopted a 95% confidence level, a typical value in hypothesis testing. Hence, the result of the test is reliable. Furthermore, both samples had at least five defective and five non-defective items. Hence, the test could use the normal approximation of the binomial distribution to determine the confidence interval. Moreover, the two-sample % defective test indicated the sample size is sufficient to detect a difference between the % defectives. The results of the two-sample % defective test are thus reliable and valid.

Lead time
The work sampling study consisted of just over 3000 observations. The confidence level and the number of observations allow determining the absolute error. With a 95% confidence level, the future performance of the lever consists of % ±1.5% VA time, % ±1.1% NNVA, and % ±1.1% UNVA time. These confidence intervals of the absolute error compared to the ones of the baseline performance, % ±0.6% VA time, % ±0.5% NNVA, and % ±0.5% UNVA time, reveal they do not overlap. Thus, the VA, NNVA, and UNVA percentages differ significantly between the baseline and future performance. Also, the small confidence intervals of the absolute errors ensure reliable results. However, the results are not fully valid. Some of the activity categories are underrepresented, shown in Figure 7.9. The category study has no share because employees did not have to register their working hours. The category away has a relatively low share since an assembly session took up only a short part of the day. The employees may, for example, have visited the bathroom just before or after the assembly session. Furthermore, the location of the test setup was quiet and did not represent the dynamic setting of the sheltered workshop. The employees assembled levers alone, whereas the normal background activities lacked. Thus, the results are reliable, though not fully valid, since we introduce some nuances.

Costs
The one-sample Wilcoxon test determined that the median of baseline performance is significantly larger than the median of the future performance. For this purpose, we used a sample size of 100, based on the minimum sample size and evaluation of the standard error, confidence interval of the standard error, and power values. The measured cycle times are fairly symmetrical distributed since the skewness is 0.45, given in Figure 7.14. Hence, we were allowed to use the one-sample Wilcoxon test. Otherwise, the one-sample sign test would have yielded a similar result: a p-value of exactly zero and a power value of precisely one. The results are therefore reliable. Unfortunately, similar to the validity of the lead time, nuances of the results affect the validity. The dynamic setting of the sheltered workshop lacks, and some of the activity categories are underrepresented because the assembly session took up only a short part of the day.

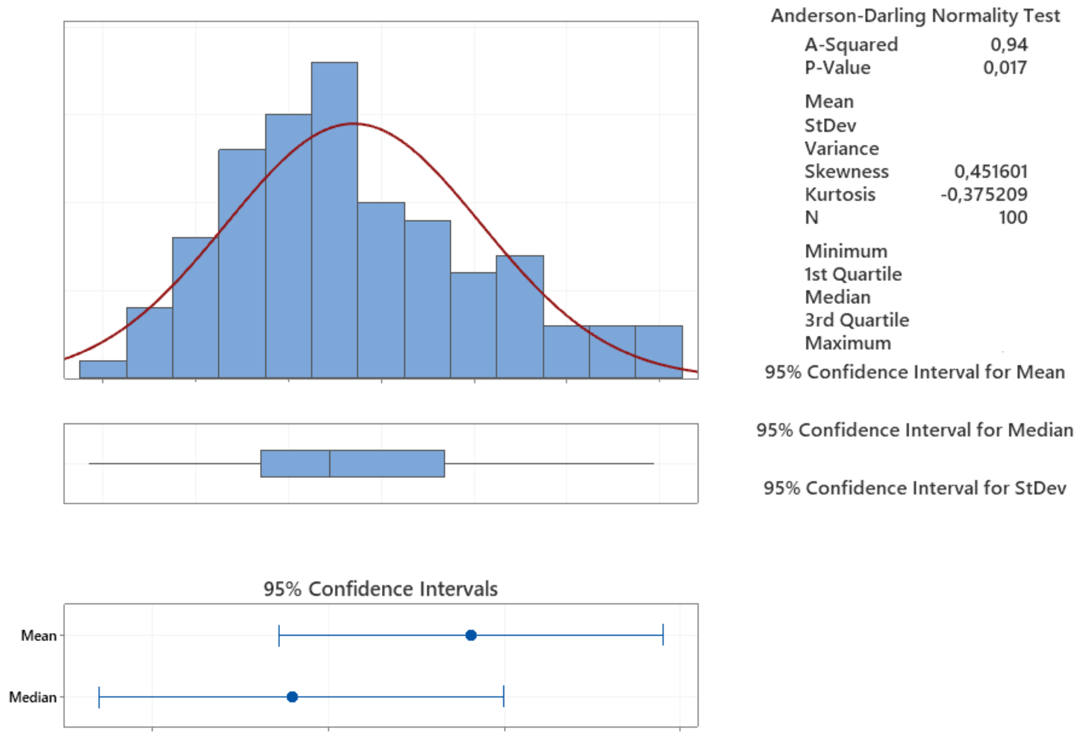

Figure 7.14: Graphical summary of the 100 lever cycle times.

Ergonomics

The two ergonomic checklists determined risk assessment scores using different questions for similar aspects. Both independently indicated there is no need to perform detailed analyses of the new process design. In addition, the risk assessment scores in the Fysisnel are once more high, meaning the ergonomic conditions should be good. So, the results are reliable. Furthermore, the training in working postures during manual pressing tackled the cause of the current health complaints. However, health complaints develop over time and do not occur immediately. As mentioned for some working postures, we could not exactly determine how frequently the employees perform certain activities per hour. Therefore, health complaints caused by bad working postures may emerge among the employees only after implementation. Thus, the results are reliable, but we cannot comment on their validity, as we cannot diagnose long-term health complaints in the short term. Active monitoring of the ergonomics and potential health complaints is recommended.

7.5 Workload balancing

The expected performance of the lever assembly in the future state is determined. In addition, the production process design of the lever is flexible to changeover relatively quickly between the different lever varieties. However, it also has to be flexible to cope with variability in the workload. Increasing the capacity of a process by adding additional employees to the assembly process is a solution to cope with workload variability. Nevertheless, the workload between employees should not differ too much. Therefore, subsection 7.5.1 mentions three potential operating modes to balance the workload and afterwards selects one. Next, 7.5.2 proposes the workload balancing for the lever assembly in the future state.

7.5.1 Operating mode

Three operating modes are possible to balance the workload between the employees. These modes are the rabbit chase, bucket brigades, and baton touch. Section X.1 in Appendix X elaborates on the three operating modes. The evaluation of the operating modes resulted in the selection of baton touch. Baton touch has a larger balancing potential since it does not necessarily require assigning employees to consecutive workstations. Furthermore, the rabbit chase and bucket brigades likely cause more productivity loss due to their operating principles and requirements in communication and coordination. Section X.1 in Appendix X discusses the evaluation and selection of the operating modes in more detail.

7.5.2 Balancing assembly line

Balancing the workload of the lever assembly process in a baton touch operation mode is similar to a type II assembly line balancing problem. Given the number of workstations, minimise the cycle time or maximise the output rate (Grzechca & Foulds, 2015). There is a large body of scientific literature covering the subject of assembly line balancing. It includes numerous problem-solving methods (e.g., heuristics) in a deterministic or stochastic setting. However, balancing the workload of the lever assembly was an exploratory study as assembly line balancing is not the main focus of this research. In addition, the number of workstations is only nine, and thus the solution space is small. Important to that note the nine workstations are for assembling standard levers. The clip bar levers follow the same assembly sequence but have one subsequent assembly step. In addition, the standard levers account for % of the annual production quantity. Hence, the study did not formulate and solve a mathematical model given the low number of workstations. It used the deterministic mean processing times per process step of the proof of concept (future state) to balance the workload.

The workload balancing started with the situation where two employees assemble levers, and the cycle time in the future state is minutes, determined in subsection 7.4.3. Then, each employee would ideally have a workload of minutes. Given that the processing times of the first three assembly steps are all slightly under minutes (Figure 7.11), the target was a balancing line of minutes. However, combining one of these three assembly steps with the last two assembly steps results in more than minutes. To overcome this issue, we mentioned four aspects to consider in the future state of the lever assembly process. They were the continuation of the learning curve, use of tuflok screws, industrial-grade fixtures and tooling, and redesign of the engineering fit between the bush bearings and the pivot block. Section X.2 in Appendix X elaborates on these four aspects and their (expected) reduction in the processing time per assembly step. The four aspects resulted in an expected cycle time of the lever of minutes, and thus employee would ideally have a workload of minutes. After evaluation of potential assembly step combinations, the criterion that states minimise the walking distance (listed in subsection 6.1.2) was decisive. Balancing the workload over two employees results in employee one performing the first and second assembly steps and the second employee performing the third to fifth assembly steps. Figure 7.15 visualises the workload balancing and shows only a minor balancing loss. It has a balancing line of minutes to overcome the variation in processing times in a sheltered workshop discussed in Section X.1 in Appendix X.

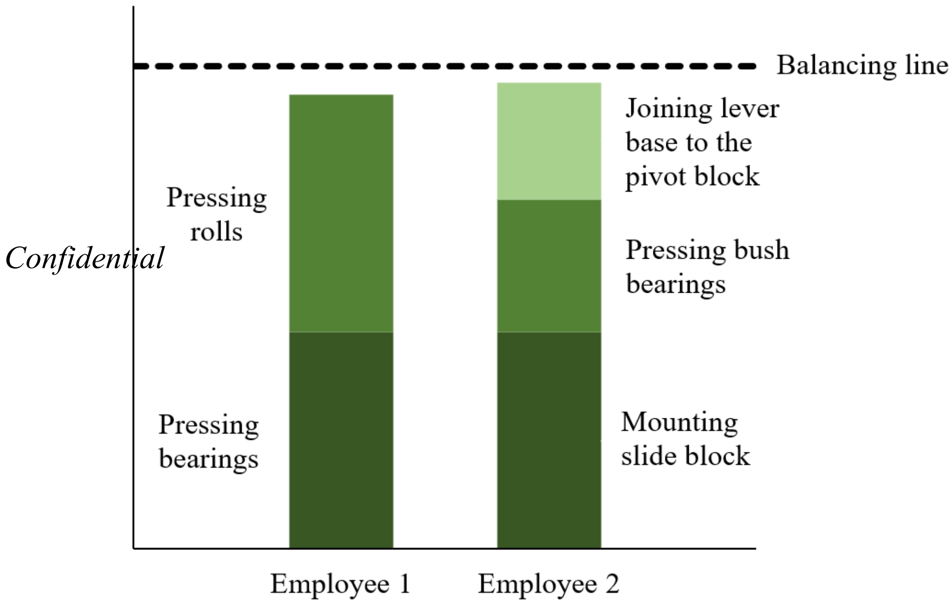

Figure 7.15: Work balancing with two employees in the future state of the lever assembly process.

The presented distribution of assembly steps balances the workload very evenly between the two employees. We did not perform any workload balancing with three or more employees. The reason is the expected capacity of the process. The new process capacity has an output rate of standard levers per hour and slightly more than thousand per year when only one employee assembles levers. In addition, when two employees assemble levers, the expected output rate is levers per hour and over thousand standard levers per year, as listed in Table 7.4. When we put the process capacities into perspective with the current demand of for all lever varieties, the capacity of the new process design of the lever is with one employee 1.7 times and with two employees 3.3 times larger than the annual demand. Thus, the process can easily handle further growth in the future, and additional balancing of the workload with three or more employees is superfluous. Section X.2 in Appendix X provides more detailed information about the expected future process capacity. When more than two employees need to assemble levers, it is wise to have four employees with a workload of about minutes assembling levers. Then, employees should frequently rotate in assembly tasks to prevent repetitive work because the dynamism of the one-piece-flow process, introduced with the new process design, is lost.

Table 7.4: Future process capacity of the lever assembly process with one and two employees.

	Effective cycle time [min]	Output rate				Annual demand	Capacity
		Hourly	Weekly	Monthly	Yearly		
1 employee							1.7
2 employees							3.3

7.6 Conclusion

The seventh chapter determined the future performance of the new lever process design. It first introduced the proof of concept and discussed the used data collection plan to determine the performance. Then, we mentioned the assembly and ergonomic training and the continuous improvement of the process design. Afterwards, we presented the future performance of the lever assembly process and discussed its validity. Lastly, we balanced the workload of the lever assembly over the employees in the future state. Thereby, the chapter answered the sixth research question: "*What is the expected performance of the new production process?*"

The feasibility of the new process design and verification of the new assembly methods was through a proof of concept. For this purpose, we experimented with a physical model of the system that represented the new production process design of the lever. We decided not to experiment with the actual system because of the substantial financial investment. Also, we did not use a mathematical model since it is hard to simulate the complex and dynamic setting of a new assembly process without any suitable input data. In the proof of concept, we evaluated the scenario where the employees assembled 100 levers of the lever variant 14"-18"-L495. We based the sample size on the minimum sample size and evaluations of the standard error, confidence interval of the standard error, and power values, using a 95% confidence level.

The data collection plan started with the same seven KPIs used for the baseline performance. They related to the CTQs quality, lead time, costs, and ergonomics. We excluded the quality KPI alignment of parts .
Assembled according to instructions, the other quality KPI used another approach (e.g., absence of repair tools, TOS, and process design) to overcome reliability and validity issues of the baseline performance. The lead time CTQ with the KPIs VA, NNVA, and UNVA time again used work sampling since the results of the first process measurement were accurate and valid. We generated new cycle times to calculate the assembly costs of the baseline performance using a Monte Carlo simulation. The original cycle times were unreliable and invalid. A direct time study determined the cycle times in the proof of concept. Also, we again used the ergonomic checklists to examine the ergonomics scores. To overcome the validity issues of the baseline performance, the new process design and ergonomic training tackled the cause of the validity issues.

Before the process measurement, the employees had a training week. The objective was to improve the reliability and validity of the process measurement. Also, the training week improved the process design through a continuous improvement board. The board visualised employee suggestions, and we implemented half of these suggestions.

The number of quality issues on the TOS was at the end of the proof of concept. of these issues required repair since we counted the number of repairs similar to the baseline performance. The repairs resulted in a lever assembly FTR percentage of %, which is % greater than the FTR percentage of the baseline performance. The results are reliable and valid. We ruled out the possibility of conforming levers assessed as non-conforming, and it is unlikely that the employees assessed non-conforming levers as conforming. The new process design has reduced the probability of questionable process quality. The two-sample % defective test determined the defective rate of the baseline performance is significantly greater than the defective rate of the future performance. A confidence level of 95% ensured a reliable result. Also, we met the test conditions and had a large sample size to ensure a reliable result.

The future state lever assembly process has a % VA percentage. It is % higher than the baseline performance. Simultaneously, the time spent by employees on NNVA and UNVA activities decreased by % to % and % to %, respectively. The confidence intervals of the absolute errors were small and they did not overlap with the ones of the baseline performance. It ensured reliable results. However, the results were not completely valid. The dynamic setting of the sheltered workshop lacked. Moreover, some of the activity categories were underrepresented because the assembly session took up only a short part of the day.

The effective cycle time reduced by almost % from minutes to minutes, which equals a capacity increase of the process by %. Hence, the assembly costs of a standard lever decreased from € to € per lever, a saving of € per lever. Moreover, the one-sample Wilcoxon test determined that the median of baseline performance is significantly larger than the median of the future performance. We met the conditions to perform the test, and a p-value of precisely zero and a power value of precisely one assured a reliable result. However, the same nuances as the lead time (e.g., absence of sheltered workshop dynamism and underrepresented activity categories) impact the validity.

The ergonomic checklists concluded that there is no need to perform detailed analyses of the lever assembly. The results are reliable because both ergonomic checklists independently determined the good scores using different questions for similar aspects. However, health complaints develop over time and do not occur immediately. We can only assess the validity of the results after implementation. Therefore, we cannot comment on the validity because we could not diagnose long-term health complaints in the short term.

We balanced the workload by first selecting the operating mode baton touch and subsequently balancing the workload evenly over two employees. Baton touch has a larger balancing potential since it does not necessarily require assigning employees to consecutive workstations. In addition, the rabbit chase and bucket brigades likely cause more productivity loss due to their operating principles and requirements in communication and coordination. Evaluation of potential assembly step combinations resulted in one employee performing the first and second assembly steps and the second employee performing the third to fifth assembly steps since it minimises the walking distances. We did not perform any workload balancing with three or more employees. The capacity of the new process design of the lever is with one employee 1.7 times and with two employees 3.3 times larger than the annual demand. Thus, the process can easily handle further growth in the future.

The proof of concept demonstrated the feasibility of the new process design, and the new assembly methods worked as intended. However, this was only for one lever variant. Hence, we have to outline the activities to make the process design suitable for all lever varieties. For this purpose, we draft in the next chapter an implementation plan. It outlines all the activities VMI should carry out to realise and further improve the process design of the lever. Furthermore, it evaluates the required investments and savings of the new process design.

8 Solution implementation

The eighth chapter outlines the approach to implementing the new process design of the lever. It first discusses the implementation plan in Section 8.1. Then, Section 8.2 determines the financial feasibility of the new process design by evaluating scenarios in cost-benefit analysis. Finally, Section 8.3 finalises the chapter with a conclusion of the main findings.

8.1 Implementation plan

The implementation plan lists all the activities VMI needs to carry out to implement and further improve the new process design of the lever. It consists of pre-implementation activities, actual implementation, and post-implementation activities. Subsection 8.1.1 discusses the pre-implementation activities. Then, subsection 8.1.2 elaborates on the actual implementation. Subsection 8.1.3 mentions the post-implementation activities. Lastly, subsection 8.1.4 schedules the implementation activities in a roadmap.

8.1.1 Pre-implementation activities

The pre-implementation activities address activities for the departments engineering, production engineering, supervisor production group E720, and warehouse. The following paragraphs discuss the activities per department.

Engineering

Engineering has to carry out the three activities that define quality standards, review engineering fits, and redesign the engineering fit between the pivot block and the bush bearings. Quality standards resolve the issues encountered in the MSAs:
results in employees struggling with whether a lever passes inspection or needs rework. Hence, engineering has to list the aspects of lever employees should check and specify per aspect when a lever passes or fails. These standards should be simple and preferably of a visual nature to co-operate with the sheltered workshop. As a suggestion, we introduce a quality standard to replace the swinging employees perform after joining the lever base to the pivot block, discussed in assembly step four of Appendix F. Given the new assembly method uses no adhesive to secure the bush bearings (mentioned in subsection 6.2.4), the result is that the lever rotates more smoothly in the pivot block. There is more clearance between the bush bearings and the lever, resulting in far less resistance. The resistance is so low that the gravitational force of the pivot block causes it to tip forward in the new bin arrangement of subsection 6.7.2. Figure 8.1 visualises the difference in resistance: the lever on the left used no adhesive to secure the bush bearings, whereas the lever on the right used adhesive. We suggest the quality standard as the pivot block has to tip forward when starting in a level position. We recommend engineering starts defining standards for one lever variety, preferably the lever with the highest demand: the 14"-18"-L495 standard lever. Afterwards, it specifies the quality standards for all standard levers and finalises the quality standards with the addition of the clip bar levers. The estimated workload for defining the quality standards is 40 hours and can start immediately.

Figure 8.1: Difference in resistance between glued (r) and unglued bush bearings (l) causing the pivot block to tip forward (l) or not (r).

The second activity for engineering is to review the component design . The engineering fit between the pivot block and bush bearings issue is an example and discussed hereafter. However, more components suffered from component quality issues, elaborated in subsection 7.4.1. The TOS meeting revealed that most of these issues originate from the engineering fits between the shaft and ball bearings and the rolls and shaft/bush. Therefore, engineering has to review if the engineering fits between the mating components are appropriate for fulling the function for which they were designed. Furthermore, we suggest engineering reviewing the remaining engineering fits of the lever as a recommendation. It should be sufficient to review one lever variety since the results apply to all other varieties. The expected workload for reviewing the engineering fits is 10 hours and can begin directly.

The third aspect is redesigning the engineering fit between the bush bearing and the pivot block. Subsection 7.2.1 mentioned . We suggest the following procedure to overcome this issue. First, engineering has to propose a new design for the engineering fit, . Then, we suggest ordering a batch of pivot blocks to test the new design. The hole in the pivot block should secure the bush bearings but not deform the bearings too much such that they interfere with the dowel. If the new design works as intended, engineering can change the design of the other pivot block varieties. Otherwise, the design may need additional altering, . When the designs of all pivot blocks have improved, VMI can change the standard. Hence, in the engineering phase of a drum, the new pivot blocks are standardly used, and the employees use them for the lever assembly. The estimated workload for changing the engineering fit between the bush bearing and the pivot block is 40 hours and should start as soon as possible.

Production engineering

The activities for production engineering are the industrialisation of the process design and implementation of the TOS concept. The industrialisation of the process is the further development of the lever process design. We used prototypes of fixtures, pressing tools, and tooling in the proof of concept. They require industrial-grade equivalents for daily use. The tooling consists of selecting a manual press type and the prototype of the last assembly step. The latter demonstrated its working principle and stunning improvement in process quality in the proof of concept. However, the tooling demands a stronger and stiffer frame since it already required strengthening during process measurement. The selection of manual press type refers to the various types of presses of different firms used in the proof of concept. One of them, given on the left in Figure 8.2, has preferable features. It has adjustable working height, a fixed outreach, and a spring-loaded handle. These features are preferable since they improve working conditions and help improve process quality. Therefore, production engineering should review potential manual presses because not every manual press has these features. For the pressing tools, production engineering should define an appropriate steel alloy. Moreover, engineering has to approve and assign a (drawing) number to every tool. A number eases the ordering of replacements. Furthermore, we developed fixtures for the lever range 14"-18". They worked as intended, but production engineering needs to define an appropriate steel alloy. Therefore, we recommend detailing the developed fixtures first. Subsequently, engineering has also to approve and assign a (drawing) number to every fixture. When detailing of the first lever range has finished, production engineering should continue with the lever range 19"-24". It designs SMED and poka-yoke fixtures following the same procedure, as discussed in subsection 6.5.1. The lever range 12"-13" follows afterwards, and the mentioned procedure repeats. Then, the process design can assemble all standard levers,   % of the annual demand. Production engineering can include the remaining   % by adding one assembly step to the process design for the clip bar levers. As mentioned in subsection 6.2.4, the clip bar levers follow the same assembly sequence but have one subsequent assembly step. Given this assembly step was not part of the proof of concept, we recommend testing the workstation design. Testing can eliminate major issues occurring immediately after implementation. The final aspect to consider is the type of workbench to use. The proof of concept used standard, wooden top workbenches. However, for daily use, steel top workbenches are, for instance, more appropriate given their strength. When production engineering has finished all these aspects, it has to write an investment proposal to initiate the purchase of the process equipment. The expected workload for industrialisation of the process lever design is 100 hours and can start immediately.

Figure 8.2: Difference between manual press types: left press with adjustable working height, fixed outreach, and spring-loaded handle and the right press having none of these features.

The second aspect is the implementation of the TOS, as the current process suffers from component and quality issues. Application of the TOS concept, introduced in Section 6.6, can already start solving these issues. We recommend focusing only on component quality since the new process design tackled most process quality issues. Furthermore, most quality issues in the proof of concept were related to component quality, as discussed in subsection 7.4.1. We suggest starting with a weekly TOS meeting for root-cause analyses. The meeting should consist of a manufacturing engineer and the employees and supervisor of the sheltered workshop. Production engineering shares the results of the analyses with the department(s) responsible. The implementation should also include using the KPI cost of poor quality. It registers the replacement components, which prevents discrepancies between the physical and ERP inventory. The estimated workload for applying the TOS concept is two hours weekly, and the actual implementation should be as soon as possible.

Supervisor production group E720

The supervisor of production group E720 has to create a skill matrix of the sheltered workshop employees who assemble levers. The skill matrix lists per employee the tasks he or she can perform and their level of expertise. The latter can, for example, range from the employee can perform the task with support to the employee being able to train others for the task. The primary reason for creating a skill matrix is the results of the swimlanes, discussed in subsection 4.2.2. For instance, it revealed that not every employee has the same skillset for performing repairs. After creating the skill matrix, the supervisor can determine which employee needs additional training. We recommend that every employee can at least perform three tasks of the process, and every task can be performed by at least three employees: the 1:3 / 3:1 rule. Hence, it ensures continuity of the process in the case of (prolonged) absence of employees. The expected workload for creating a skill matrix and training employees is eight hours and can begin directly.

Warehouse

The warehouse organises the information and material streams of the new process design. It includes extending the milk run, implementing the two-bin Kanban system, organising the material supply of sporadic lever varieties, and structure backflush for the consumed components. The latter requires changes of settings in the MPS and ERP system, safety stock levels, minimum order quantities, and forecasting intervals, for instance. Another aspect is the number of levers per PO should reduce to 15, the maximum number of levers per bin, introduced in subsection 6.7.2. The final aspect is the scheduling of POs. The relatively fast changeover times of the new process design, the Heijunka box, and the significant reduction of the lever cycle time allow mixing lever varieties and levelling demand. The warehouse employees should place the bins evenly in the weekly schedule to balance the workload. The estimated workload is 20 hours, and organising the information and logistics streams can start immediately. When production engineering has finished the process design of the lever, the organisation of information and material streams may require slight changes.

8.1.2 Implementation

We recommend implementing the new process design of the lever in two steps. The first step implements a process design only for the assembly of the standard levers. Then, the process design is similar to the test setup. Simultaneously, the current process and shelf racks are dismantled to create space for the new process. In the weeks leading up to the implementation, it may be wise to stock levers of high demand. It acts as a buffer to overcome issues that may occur in the first weeks after implementation. When the assembly of the standard levers operates smoothly, the second step of implementation follows. Adding the workstation that finishes the clip bar levers. Note that by this time, the employees already have used the new assembly process to assemble clip bar levers, but they could not perform the final step of the assembly process. If the recommended pre-implementation tests have been carried out, the workstation design should not pose any major problems. The expected workload for implementing the new process design of the lever is 80 hours and can only start when all the pre-implementation activities have been performed.

8.1.3 Post-implementation activities

The post-implementation activities address activities only for the departments engineering and production engineering. The following paragraphs discuss the activities per department.

Production engineering

The activities for production engineering are creating a capable process and active monitoring of ergonomics. The first aspect relates to the continuous improvement maturity model (CIMM). The new process design of the lever is a stable and predictable process, which is equal to the third level in the CIMM. However, production engineering should focus on creating a capable process, the fourth level in CIMM. The fourth level aims to reduce variation and improve (process) quality (Theisens, 2017). Variation reduction refers to the root-cause analysis of outliers in the cycle times. For instance, the outliers in the future state of Figure 7.12. If production engineering can eliminate the causes, the cycle times follow a normal distribution, given in Figure Y.4 of Appendix Y. Important to note that the outliers all relate to the engineering fit between the bush bearings and the pivot block. Thus, when engineering solves this issue, the cycle times already follow a normal distribution. Appendix Y elaborates on variation reduction. It outlines the used approach and presents the results that provide normally distributed cycle times.

The TOS improves the process quality. Implementation of the TOS concepts is, as discussed in subsection 8.1.1, part of the pre-implementation phase and focused on component quality. However, the TOS meetings are extended with the root cause analysis of process quality when the process design is implemented. Immediately after the first step of implementation, we recommend organising a daily TOS meeting between a manufacturing engineer and the employees and supervisor of the sheltered workshop. In the starting phase of lever assembly, minor issues will likely emerge. Hence, organising a daily TOS meeting is logical. When the TOS has only a limited number of rejected components and levers over longer periods, the TOS meeting can become a weekly meeting. The estimated workload shortly after process implementation is four hours per week. After the reduction of variation and quality issues, the expected workload is one hour per week.

The active monitoring of ergonomics is one of the outcomes of the ergonomics study, discussed in subsection 7.4.4. We could not exactly determine some aspects of the ergonomic checklists and could not diagnose long-term health complaints in the short term. Therefore, we recommended active monitoring. Production engineering should keep in close touch with the sheltered workshop employees. It keeps the employees involved in continuous process improvement, introduced in subsection 7.3.3. Moreover, production engineering can detect ergonomics issues quickly and act appropriately. For example, it may be wise to repeat periodically the ergonomic training mentioned in subsection 7.3.2. A weekly conversation with the sheltered workshop employees and observations on working postures should be sufficient for active monitoring of ergonomics. Hence, the expected workload is 15 minutes per week and starts immediately after process implementation.

Engineering

The post-implementation activity of engineering is the redesign of the slide blocks. In subsection 6.2.4, we presented a new design of the slide block that reduces the assembly time, improves working conditions, and improves the ease of assembly. The design change is financially viable, but we questioned the technical feasibility. Therefore, engineering should first review the design proposal of one slide block, which is used for a standard lever, and approve it for testing. The testing is an endurance test and repeats the daily use of levers and thus slide blocks tens of thousands of times. It is important to note that the levers in the endurance test must have the redesigned engineering fit between the bush bearings and pivot block. The difference in resistance between glued and unglued bush bearings may have a significant impact on the technical feasibility. Furthermore, it is wise to include the tuflok screws in the endurance test to examine their suitability. If the new slide block design does not cause any issues, engineering can change the design of all the slide blocks used for standard levers. Otherwise, the design may need additional changes and repetition of the endurance test. The slide blocks for clip bar levers may not be suitable for a redesign since they have an extra function. Engineering has to review these slide blocks before a potential redesign. When all slide blocks or only a selection of slide blocks are technically feasible, engineering can change the standard. Also, when the tuflok screws did not cause any issues during the endurance test, they can become part of the standard. Hence, in the engineering phase of a drum, the new slide blocks and tuflok screws are standardly used, and the employees use them for the lever assembly. The estimated workload for redesigning the slide blocks is 60 hours and can only start when engineering has finished the redesign of the engineering fit between the bush bearings and the pivot block.

8.1.4 Implementation roadmap

Figure 8.3 overviews of all the pre-implementation activities, actual implementation, and post-implementation activities VMI needs to carry out to implement and further improve the new process design of the lever. The expectation is that VMI can implement the new process design of the lever in the third quartile of 2022. Moreover, we expect that production engineering finishes the further improvement of the process design by the end of the first quartile of 2023.

Implementation phase	Department	Activity	2022				2023
			Q1	Q2	Q3	Q4	Q1
Pre-implementation activities	Engineering	Define quality standards					
		Review two engineering fits					
		Engineering fit bush bearings/pivot block					
	Production engineering	Industrialisation process design					
		Implementation TOS concept					
	Sheltered workshop	Skill matrix					
	Warehouse	Information and material streams					
Implementation	Production engineering	Process design standard levers					
		Process design clip bar levers					
Post-implementation activities	Engineering	Redesign slide blocks					
	Production engineering	Create capable processes					
		Active monitoring ergonomics					

Figure 8.3: Implementation roadmap for the production process design of the lever.

8.2 Cost-benefit analysis

To determine if an investment in the new process design of the lever is sound, we compared the total expected cost with the total expected benefit using a cost-benefit analysis. The cost-benefit analysis evaluated three scenarios:

- **Scenario 1:** Process design
- **Scenario 2:** Process design + pre-implementation activities engineering
- **Scenario 3:** Process design + pre-implementation activities engineering + design change slide block

We selected the second scenario as the business case since production engineering and engineering have already initiated the redesign of the engineering fit between the bush bearing and the pivot block. Also, engineering questioned the technical feasibility of the slide block redesign. Hence, the second scenario is the most realistic. Appendix Z details the three scenarios and lists in Figure Z.1 to Figure Z.3 the costs and benefits per scenario. Table 8.1 summarises the non-recurring costs and the annual benefits of the second scenario. It also lists improved health and safety conditions, which are intangible and thus not expressed in a saving.

Table 8.1: Cost-benefit analysis of the second scenario.

Non-recurring costs		Annual benefits	
Process equipment	€	Man-hours	€
Man-hours	€	Materials	€
Materials	€	Improved health and safety conditions	-
Unforeseen	€		
Total	€	**Total**	€

The annual benefits of € outweigh the non-recurring costs of € and result in an expected return on investment (ROI) of months. An ROI of months is quick and demonstrates the great potential of the new process design. Therefore, we can conclude that the new process design of the lever is both technically and financially feasible. Table 8.2 lists the costs, benefits, and ROIs of all three scenarios. It shows that if the design change of the slide block is technically feasible, the annual benefits can potentially become over € . Moreover, the ROI only increases by months.

Table 8.2: Overview of the costs, benefits, and ROIs per scenario.

	Non-recurring costs	Annual benefits	ROI [months]
Scenario 1	€	€	
Scenario 2	€	€	
Scenario 3	€	€	

8.3 Conclusion

The eighth chapter outlined the approach to implement the new process design of the lever. It first discussed the implementation plan. Secondly, it evaluated in multiple scenarios the costs, benefits, and ROI of the process design of the lever. Hence, the chapter answered the seventh research question: "*How should the new production process design be implemented?*"

The implementation plan lists all the activities VMI needs to carry out to implement and further improve the new process design of the lever. It consists of pre-implementation activities, actual implementation, and post-implementation activities. Every implementation phase lists the departments (i.e., engineering, production engineering, supervisor production group E720, and warehouse) and their activities. Figure 8.3 visualises the implementation plan using a roadmap. It expects that VMI can implement the new process design of the lever in the third quartile of 2022. Moreover, it expects that production engineering finishes the further improvement of the process design by the end of the first quartile of 2023.

The cost-benefit analysis evaluated the three scenarios where the first is equal to the process design in the proof of concept. The second also incorporates the pre-implementation activities of engineering, including redesigning the engineering fit between the bush bearings and pivot block. The third scenario is the second scenario with the addition of the design change of the slide block. We selected the second scenario as the business case since VMI already initiated the redesign of the engineering fit between the bush bearing and the pivot block. In addition, engineering questions the technical feasibility of the third scenario. It has annual benefits of over € , non-recurring costs of about € , and an ROI of months. An ROI of months is quick and demonstrates the great potential of the new process design. Furthermore, we conclude that the new process design of the lever is both technically and financially feasible.

The drafted implementation plan and determining the financial feasibility were the last aspects of the production process design of the lever we needed to detail. Therefore, the next chapter presents the conclusions and recommendations, and discusses the results.

9 Conclusions and recommendations

The ninth chapter finalises the research. It first presents the main conclusion of this research in Section 9.1. Then, Section 9.2 discusses the research results. Finally, Section 9.3 presents recommendations for VMI.

9.1 Conclusions

The sheltered workshop of VMI has production group E720 for the mechanical assembly of high-volume, low-variety products. To prepare the sheltered workshop for the future, VMI desires to realise high-capacity production processes in the short term. Therefore, we considered one of its production processes a toy problem to demonstrate and exercise various methodologies for the other production processes. Hence, the objective of this research was to answer the following main research question:

How can a specific pilot production process of production group E720 be redesigned such that the annual production capacity increases considerably while the number of employees remains intact?

The product selection selected the lever for a new production process design. Firstly, the lever has growth and potential. Secondly, it has by far the largest share in production hours and quantities of any product in the product portfolio. Thirdly, it is an IP-related product, which means the assembly of levers will remain in Epe for years. The lever assembly is a batch process and has its dedicated production cell in the facility. The MPS controls the material supply and schedules POs per week. Shelf racks close to the lever production cell store the components needed for the POs. The current performance of the lever production process has a % FTR percentage, and the assembly time consists of % VA, % NNVA, and % UNVA activities. Furthermore, the assembly costs for a standard lever, mechanical, and vacuum clip bar lever are € , € , and € , respectively. Finally, the ergonomics of the lever assembly are good because two ergonomic checklists separately indicated that the workload should not cause any health complaints. Table 9.1 lists the current state performance of the lever assembly process and the requirements of VMI per KPI. These results proved that the current performance of the lever production process does not meet the specified requirements in terms of quality, lead time, and costs.

Table 9.1: Overview of the current state performance of the lever assembly process.

	Quality	Lead time			Costs			Ergonomics
KPI	FTR-%	VA-%	NNVA-%	UNVA-%	Assembly costs			Ergonomic score
					S	M	V	
Req.	%	≥ %	≤ %	≤ %	€	€	€	-
Current state	%	%	%	%	€	€	€	Good

We designed a new production process design for the lever. We developed solutions that can potentially solve up to 77% of the current issues. These issues relate to facility layout, material supply, process and workstation design, and work method. The remaining percentage mainly consists of out-of-scope issues and a non-influenceable process characteristic. To develop the new production process design, we followed a framework described in the literature. It yields a new process design where the most fundamental changes are that the process becomes a mass process with a product layout. Furthermore, the lever assembly is a one-piece flow process arranged in a U-shaped layout. The new design also includes new assembly methods that should significantly improve the working conditions, ease of assembly, and process quality. The material supply consists of two streams, where the first delivers two components of levers varieties with intermittent demand equal to the demand. The second supplies the other components using a two-bin Kanban system, which accounts for % of the annual demand. Furthermore, we introduced the TOS as a continuous quality improvement concept for the process and component quality. Lastly, it includes improvements in ergonomics, quality improvement cycle, scheduling, and workstation design.

A proof of concept determined whether the new process design of the lever is feasible and verified if the new assembly methods work as envisioned. We experimented with a physical test setup that represented the new process design. The proof of concept used a sample size of 100 standard levers, determined using a 95% confidence level. Table 9.2 presents the future performance of the lever assembly process. It indicates that the FTR percentage increased by % to %. Furthermore, the future state lever assembly process has a % VA percentage, a plus of %. Simultaneously, the NNVA decreased by % to %, and the UNVA declined by % to %. In addition, Table 9.2 lists a decrease in the effective cycle time from minutes to minutes per standard lever. Hence, the assembly costs reduce from € to € per lever, a saving of € per lever. Moreover, the workload of the lever assembly should not cause any health complaints since the ergonomics of the new lever assembly process are good. The most important result is that our approach resulted in a capacity increase of % when only one employee assembles levers. This new process capacity is already 1.7 times larger than the current demand for levers.

The implementation plan consists of the three phases pre-implementation, implementation, and post-implementation. We estimated the annual benefits and the non-recurring costs of these activities and the purchase of the process equipment for three scenarios. We selected the second scenario since it is the most realistic scenario. The second scenario expects € of non-recurring costs and € of annual benefits. It results in an ROI of months. Thus, we can conclude that the new process design of the lever is both technically and financially feasible.

Table 9.2: Overview of the current state and future state performance of the lever assembly process.

	Quality	Lead time				Costs	Ergonomics
KPI	FTR-%	VA-%	NNVA-%	UNVA-%	CT [min]	Assembly costs	Ergonomic score
Req.	%	≥ %	≤ %	≤ %		€	-
Current state	%	%	%	%		€	Good
Future state	%	%	%	%		€	Good
Delta	+ %	+ %	- %	- %	-	-€	-

We considered the lever assembly process a toy problem for the other production process of the production group E720. Applying the various methodologies resulted in a technically and financially feasible new process design. Hence, we demonstrated that, for example, the production processes of the canister or pallet can use a similar approach to realise a considerable capacity increase.

9.2 Discussion

The reliability and validity of the current and future state performance are the main points to discuss. The current state performance had issues related to the quality, costs, and ergonomics. The reported quality issues were a lower bound due to unreported quality issues and inaccuracy of the employee to the known standard. Fortunately, the new process design and absence of repair tools did result in reliable and valid future state results. In addition, a statistical test determined a significant reduction in the number of repairs, and thus the statement that we more than the number of repairs definitely holds. In addition, the data used to determine the assembly costs for the current state had high numbers of unrealistic outliers. To overcome this issue, we performed a Monte-Carlo simulation. To the best of our knowledge, the results were a valid substitute for the current state data. Unfortunately, the future state costs were also not completely valid. The proof of concept lacked the dynamic setting of the sheltered workshop, and some activity categories were underrepresented. However, the impact of these nuances on the performance is relatively small. The four aspects mentioned for the workload balancing (subsection 7.5.2) are more than sufficient to counter the additional cycle time. Moreover, the ergonomics had issues with validity since the ergonomic checklists do not account for the individual way of working. Therefore, training in working postures tackled the cause of the validity issue. Unfortunately, health complaints, the validity cause, develop over time and do not occur or resolve immediately. To overcome this issue, we recommended active monitoring of the ergonomics. The discussion mentioned several points that impact the results of the research. However, perspective is of great importance. The new production process design of the lever has a capacity times larger than the current process has. It is worthwhile discussing these points, but they do not change the unprecedented improvement that the new lever assembly process has realised.

Another aspect to discuss is the component quality in relation to the number of NCPs. In the initial phase of the research, we excluded component quality given the low number of NCPs production group E720 reported. Unfortunately, back then, we did not know what the high inventory levels and NCP threshold for high-volume components value hide. Moreover, we did not know the high impact of an NCP since it generally concerns a complete batch of components. Therefore, we introduced the TOS concept to tackle component and process quality issues. It fills a gap in the way VMI currently uses NCPs.

9.3 Recommendations

Based on our research, we present process design related recommendations in subsection 9.3.1 and general recommendations in subsection 9.3.2.

9.3.1 Process design related recommendations

The recommendations related to the process design of the lever are the following:

- The component quality proved to be a concern throughout the research. Analysis revealed that most issues related to the engineering fits. In particular, the engineering fit between the pivot block and the bush bearings was an issue of significant concern. Therefore, we already mentioned reviewing or redesigning three engineering fits in the implementation plan. However, given the findings and the high number of engineering fits in the lever, we recommend assessing all engineering fits. Hence, ensuring that they are appropriate for fulfilling the function for which they were designed.

- The MSA revealed that results in employees struggling with whether a lever passes inspection or needs rework. Hence, the implementation plan mentioned that engineering has to list the aspects of the lever employees should check and specify per aspect when a lever passes or fails. In addition, the standards should be simple and preferably of a visual nature to co-operate with the sheltered workshop. We reintroduce this aspect given its great importance for the employees and product quality. It is crucial to come close to the specified zero quality defects.

- VMI can exploit the overcapacity and flexibility of the new process design to schedule lever POs daily instead of weekly. Favourable since it, for example, better aligns with the Heijunka box and reduces the lead time of a drum and spare parts POs. However, it requires an accurate forecast (e.g., daily demand of the drum workshop) and a different setup in the MPS. Although the transition to a daily schedule likely requires considerable time and effort, it is worthwhile to examine such a schedule.

- The overcapacity and flexibility of the new process design can certainly be used to formulate a new policy for the weekly schedule of the sheltered workshop. For example, the supervisor of the sheltered workshop can schedule lever assembly at the start or end of the week to compensate for the delay in other activities. Thus, we advise VMI and, in particular, the supervisor of the sheltered workshop to devise a policy to schedule all the weekly activities of the sheltered workshop, which exploits the flexibility and overcapacity of the new lever assembly process.

- The current material streams of finished levers are quite complex since different policies exist for project-based, non-projected-based, and backflush-controlled levers. Also, multiple storage locations exist for the three types of products. Especially the storage location in the drum workshop demonstrates the complexity and inconvenience since some levers are waiting inventory for many years. Hence, we recommend organising the material streams of finished levers differently. A suggestion is to supply levers together with the kit boxes for the drums and remove the storage location in the drum workshop. It is an option that can simplify the process, but better options may exist.

- To ensure the working conditions of the lever assembly process do not cause any health complaints, we included several ergonomic aspects in the process design and listed active monitoring of ergonomics in the implementation plan. Furthermore, we recommend considering adding anti-fatigue mats to the process design. Anti-fatigue mats help reduce health complaints caused by standing for long periods on hard floor surfaces. They lessen pressure on the legs, feet, and back when standing (Notrax, 2021).

- The application of pneumatic presses is another aspect to consider. Especially for the third and sixth press, a pneumatic equivalent improves the working conditions considerably. These two presses flare components and hence require the most employee strength. Moreover, pneumatic presses have a regulated pressing force, ensuring process quality. In addition, it is worthwhile to examine if a pneumatic cylinder can replace the manual press that presses the dowel into the pivot block. It may be better suited for fulfilling the function the prototype was realised for. Therefore, we advise VMI to research the possibilities of pneumatic equivalents for the third, sixth, and eighth press.

- The design process of the fixtures focused on minimising the need for reorientation of the workpiece during assembly. A simple design change of the slide block can eliminate one more reorientation. Currently, the employees fasten the screws with the roll side of the slide block on the left. However, they finish the previous step with the rolls on the right and hence rotate the lever 180 degrees. If the employees can fasten the screws from the other side, the roll side of the slide block is on the right. The design change does not yield a large reduction in the cycle time, but it mainly improves the ease of assembly. We recommend including this design change in the post-implementation activity where engineering already redesigns the slide block.

- The inclusion of the truck tyre levers in the new process design is another aspect to consider. We excluded the truck tyre levers after we determined their design and assembly process are quite different. However, an exploratory feasibility study can review the amount of effort and investment required to adapt the process design of the passenger tyre levers and include the truck tyre levers.

9.3.2 General recommendations

We present the following general recommendations for VMI:

- In the (near) future, production management desires to extend the product portfolio of the sheltered workshop. However, what defines a product as being suitable for the sheltered workshop? Currently, the product portfolio already consists of products that demand a relatively wide range of skills. Skills that not all employees possess or that require some practice to obtain. Therefore, we recommend that the consideration of adding a product to the product portfolio of the sheltered workshop is early on in its design phase to take the skill set of the sheltered workshop into account in the product design. The design of a product should reflect the skills of the sheltered workshop employees.

- In the process design, we introduced the concept of the TOS in Section 6.6 to monitor the component and process quality more closely. During the proof of concept, the TOS revealed what the high inventory levels and NCP threshold for high-volume components value currently hide. Hence, we recommend implementing the TOS concept for all high-volume processes. It fills a gap in the way VMI currently uses NCPs.

- We applied ergonomic checklists to evaluate the different aspects of the physical workload. These checklists do not require any prior knowledge of risk factors or physical workload. Therefore, we recommend that VMI adds them as a step in the development phase of new production processes. Although the process may not be too detailed, the results of the checklists give a proper indication of the expected working conditions. Hence, it offers the opportunity to perform a detailed analysis or adapt the design in the development phase. They contribute to proactively ensuring good working conditions instead of reacting to (emerging) employee health complaints.

- VMI uses a diverse range of adhesives in its assembly processes. These adhesives differ in applications (e.g., securing screws or retaining cylindrical parts) and thus in curing time. However, the employees often need the glued parts immediately and resort to an activator or fast curing adhesives. Unfortunately, these types of adhesives, and especially the activator, are often very hazardous for people and the environment. Fortunately, the use can be minimised or eliminated by either using tuflok screw or ensuring enough curing time for the adhesive. The latter means the employees can apply a less hazardous adhesive. To guarantee sufficient curing time, the assembly sequence in the work instructions has to change. They should start by instructing the employees to apply adhesive. Thus, we recommend reviewing the use of adhesives and either replacing them with tuflok screws or adapting the work instruction to ensure sufficient curing time, which allows using less hazardous variants.

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Appendix A NCP data

The first appendix provides an overview of the number of NCPs within VMI and production group E720 in Table A.1. Furthermore, it lists the number of NCPs originating from the lever assembly process and subdivides the NCPs into five categories in Table A.2.

Table A.1: Total number of NCPs within VMI and production group E720 in 2019 and 2020.

	2019	2020
Total number of NCPs within VMI		
Total number of NCPs within production group E720		
NCPs production group E720 relative to VMI	<1.5%	<1.0%

Table A.2: Total number of NCPs lever production process and their subdivision over technical NCP categories in 2019 and 2020.

	2019	2020
Total number of NCP lever production process		
1. Electronic defect		
2. Not according to specification		
3. Surface appearance		
4. Broken		
5. Other (logistical)		

Appendix B Product portfolio production group E720

The product portfolio of production group E720 consists of 15 categories. Ten of these categories are product families that mainly relate to the high-volume, low-variety IP modules. The remaining five categories are support activities for other production groups and service engineers. Figure B.1 lists and illustrates the ten product categories. The five support activities are field service, hour cards, tooling, WOP, and others.

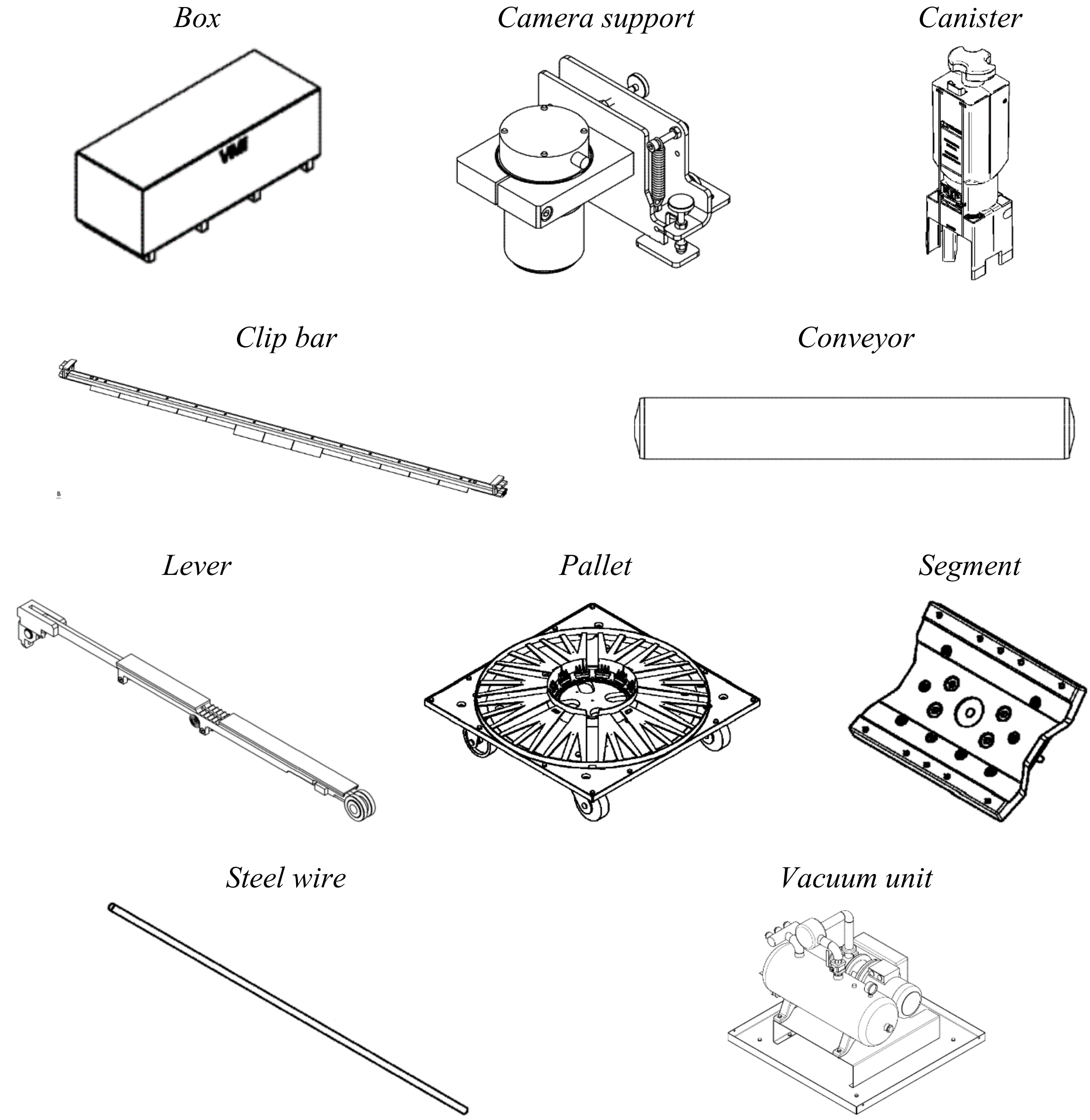

Figure B.1: Overview of the product portfolio of production group E720.

The following paragraphs discuss the categories in more detail. They mention per category a general description and the number of product varieties in the case of a product category.

Box

The category box consists of plywood boxes. They are transport boxes used to ship, for example, the carcass drum. The carcass drum is a part of the TBM. It rotates when the applicator applies layers of rubber to it to construct the tyre carcass. The production group E720 constructs these boxes and makes them suitable for transporting the module(s). The number of varieties is three, where two are of identical dimensions. The difference between these two is the material used to support the carcass drum in the box. TBMs that can produce tyres with a maximum inch size of 18 have a smaller drum than TBMs that can produce tyres with a larger inch size. The third plywood box variety has smaller dimensions and stores another module of the TBM.

Camera support
The camera support houses a camera that monitors the process quality of a TBM. Process quality assurance is a feature of the TBM, and it performs automated interventions to correct errors. The production group assembles two varieties of camera support. The difference is in the camera the support will house.

Canister
The canister is a part of the , an automated dose packaging machine. It produces daily dose pouches of medicines. In the , the canister is a storage container for one medicine. Each canister has a . The machine can hold at most 1600 of these canisters, where each medicine uses a minimum of two canisters for storage. In this way, it is hard to determine the exact number of varieties in canisters. As many as 800 different canisters per are already possible.

Clip bar
The clip bar is part of the applicator in the TBM. The applicator applies the primary layers of rubber to the carcass drum. During application, the carcass drum rotates. The clip bar prevents the primary rubber layer from falling off and misaligning. First, the clip bar detaches from the applicator and attaches to the carcass drum. Afterwards, it clips the primary layer of rubber, and the drum rotates once. Then, the clip bar attaches to the applicator, and some more rubber layers are applied. The production group E720 assembles two types of clip bars, where the difference is the width of the clip bar. TBMs that produce tyres with a maximum inch size of 18 have a smaller carcass drum and thus a smaller clip bar.

Conveyor
The conveyor is a purchased preassembled conveyor roller used in the supply of rubber in the TBM. However, the surface of these conveyor rollers needs an additional surface treatment. The employees of production group E720 disassemble the product and remove the bearings. When the part returns, the employees assemble the roller conveyor once again. Two types of conveyor rollers exist, where the difference is in the width of the conveyor rollers.

Field service
Field service is a category consisting of support activities. The employees fill steel boxes with fasteners, components, and tools. Service engineers use these boxes when installing the foundations of a TBM on-site. The production group prepares two types of field service boxes. The first one consists solely of the service box. While for the second, the employees also construct a frame. Employees mount the frame with the field service box to the frame of a finished TBM.

Hour cards
The production group E720 also logs work organising activities and non-production-related activities with hour cards. An example of a couple of years ago is the non-production-related activity of sorting sweets by colour. In the integral test of the , these sweets represent different medicines. Since the test needed a considerable number of sweets, the employees logged the required hours. The hour cards are timesheets and account for the hours.

Lever
The lever is part of the carcass drum in the TBM. During tyre building, the levers roll the layers of rubber around the beads of the tyre. A tyre bead is the edge of a tyre that sits in the groove of a rim. The air pressure within an inflated tyre keeps the bead in this groove. The production group assembles a variety of levers for different inch sizes. They are either for passenger or truck tyres. Besides, it produces some special levers, clip bar levers. When the applicator applies the first layer of rubber to the carcass drum, the clip bar attaches temporarily to these levers. Also, the employees assemble levers for previous TBM models as an after-sales service. In total, there are 21 varieties of levers.

Pallet
The pallet is a special wheeled pallet used to store the beads. A carrier stores one bead, and a pallet stores a stack of carriers. In the tyre building process, the bead loader (un)stacks these carriers and places the beads in the bead setter. The production group E720 produces three varieties of pallets as three types of carriers exist. Every carrier type can store a range of beads used for different tyre sizes.

Segment
The segment is part of the transferring in the TBM. It collects and holds the preassembled circular final tread layer. During tyre building, the segments apply this final tread layer to the tyre. Afterwards, the machine rolls it onto the tyre, which completes the tyre building. The production group mounts parts for the pneumatics and for fastening the segment to the frame of the transferring. The segments differ in width due to the different tyre widths. Furthermore, they vary in curvature due to differences in the overall diameter of the tyres. The employees assemble a total of 24 varieties of segments.

Steel wire
Steel wire secures cables and hoses in the machines. It is one of the options next to, for instance, cable ties. The production group receives bundles of steel wire and cuts the wire to three different lengths. Therefore, the number of varieties in steel wire is three. The employees place the finished wires usually in the field service boxes.

Tooling
The tooling consists of the centre decks, centre discs, and bead setters. All these parts relate to the TBM. The centre decks and discs are parts of the carcass drum. The bead setters hold the beads and apply them to the drum. After which, the levers roll the layers of rubber around the beads of the tyre. The production group E720 collects and checks these parts. The employees check, for instance, inscriptions and the quality of glueing. The employees pack the parts that are according to instructions in plastic wrap or boxes.

Vacuum unit
The vacuum unit is part of the pneumatic system of the TBM. By creating a vacuum, the segments can, for example, hold the final tread layer. The vacuum unit is a purchased assembly. The production group unpacks, connects fittings, cuts hoses to length, and attaches them to the vacuum unit. In essence, the vacuum units are the same. However, the model differs since TBMs are in use worldwide. The mains voltage and frequency, for instance, are not the same for Europe and the United States of America. The employees have worked on 12 different models of the vacuum unit so far.

WOP

WOP is an abbreviation of 'wijziging op project'. It means adjustment on a project. It applies to finished modules or products which are modified. A customer request, for example, may result in a design change. A WOP registers the additional hours needed for the modifications.

Others

The category others consists of various products. It concerns predominantly one-off products, where these products have little or no correlation with each other or with alternative categories. About 60 different products belong to this category.

Appendix C Product information lever

The inch size of the rim and the tyre's height from the rim define the lever to use in the TBM. Based on these two properties, a subdivision of the levers results in six categories, shown in Table C.1. To clarify the naming of, for example, 12"-13"-L398.5, the '12"-13"-' represents the inch size range, and 'L398.5' is the centre-to-centre distance between the pivot point and rolls. As mentioned, the rolls, mounted on the tip of the lever, roll layers of rubber around the tyre beads during tyre building. At a more detailed level, we can distinguish per category different types. There are the standard and clip bar levers. The clip bar levers temporarily hold the clip bar when the applicator applies the first layer of rubber to the carcass drum. In the current TBM, the clip bar mechanically attaches to the levers, while in the previous model, the clip bar attaches to the levers by a vacuum. Between the models, the standard levers have not changed. Therefore, the vacuum levers are an after-sales service. The mechanical and vacuum variants are sets of two times three clip bar levers. The M and the V in Table C.1 indicate that every lever category has a variety that can hold the clip bar mechanically or through a vacuum.

Table C.1: Subdivision of the levers: standard levers (S), mechanical (M), and vacuum clip bar levers (V).

Category	Types			Category	Types		
12"-13"-L398.5	S	M	V	16"-18"-L395	S	M	V
14"-17"-L395	S	M	V	19"-20"-L413	S	M	V
14"-18"-L495	S	M	V	19"-24"-L493	S	M	V

The standard lever is an assembly of 14 different components, of which six appear twice, given in Figure C.1. It has a partly modular design since the lever base (a subassembly) is used in multiple lever varieties. Table C.2, Table C.3, and Table C.4 list the parts and quantities of a standard lever and sets of mechanical and vacuum clip bar levers, respectively. Note that the same lever base returns in all three tables. Figure C.2, Figure C.3, and Figure C.4 visualise the standard lever and the mechanical and mechanical and vacuum clip bar levers, respectively.

Every lever variety has its own unique set of components. However, there are similarities between them. Within a category, the standard and clip bar levers have, except for the lever, pivot, and slide block, the same components. Moreover, between some categories, the varieties have the same pivot block, roll, shaft (roll), and bush. Additionally, all levers have eight of the same components. These are the ball and bush bearings, dowel, screws, shaft, shims, and spacer. Table C.5 overviews the number of varieties per component, and Table C.6 structures the components that distinguish the six standard levers in a flowchart.

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Figure C.1: Exploded view of a standard lever.

Table C.2: Bill of materials of a standard lever.

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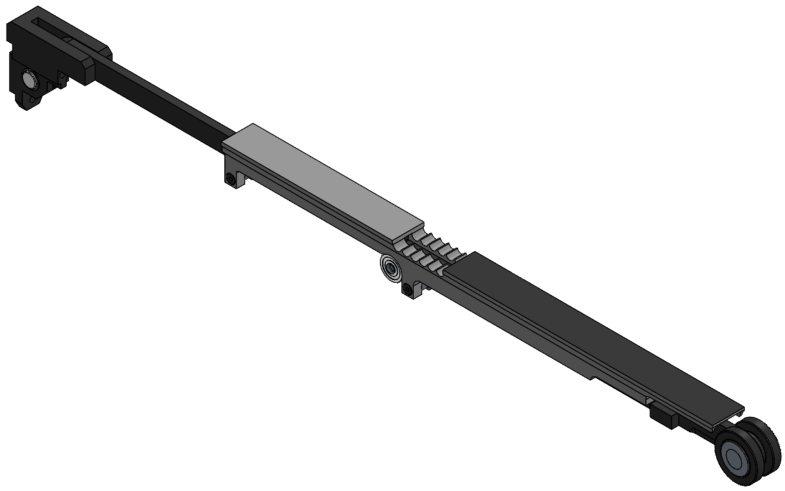

Figure C.2: Standard lever.

Table C.3: Bill of materials of a mechanical clip bar lever set.

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Figure C.3: Half of the mechanical clip bar levers in a set.

Table C.4: Bill of materials of a vacuum clip bar lever set.

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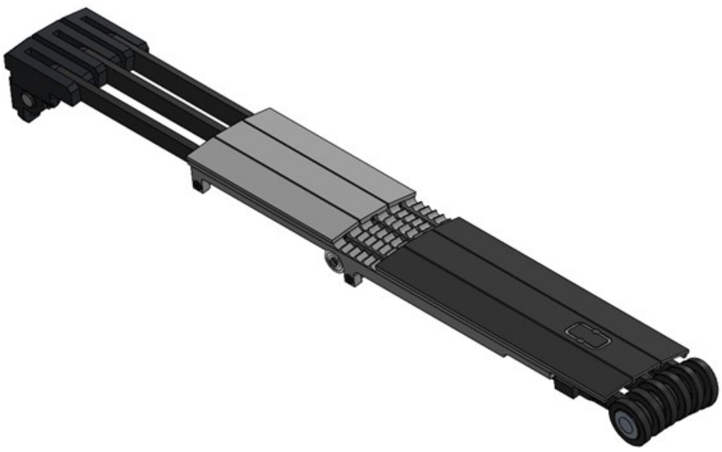

Figure C.4: Half of the vacuum clip bar levers in a set.

Table C.5: Overview component varieties of the lever.

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Table C.6: Component flowchart that distinguishes the standard levers.

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Appendix D Background process characteristics lever

To outline the production process of the lever, we use a SIPOC. We follow an approach to create a SIPOC. It starts with determining the VOB. Then, the VOB is used to create a CTQ tree. The CTQ tree translates the VOB into measurable specifications. These specifications are the process outputs of a SIPOC. Hence, the final step creates the SIPOC of the production process. It is important to note that the results of these tools are product specific as the approach already starts with determining the VOB of one product.

Voice of the business

The approach starts by determining the VOB, which defines the specifications that the business requires of the product. We use the VOB given the research scope discussed in Section 1.4. Otherwise, the approach could also start with the voice of the customer, which has a similar objective but only uses the customers to define the specifications (Pyzdek & Keller, 2003).

Critical to Quality tree

A CTQ tree translates the specifications of the business into measurable specifications. The first translation is into external CTQs, which result in measures related to the specifications of the business. The subsequent step is to translate the external CTQs into internal CTQs. These relate to what is measured of the product or process to check the product quality. The final step when creating a CTQ tree is to define the specifications of the internal CTQs. These specifications allow to determine whether the product meets the VOB (Theisens, 2017).

SIPOC

SIPOC is an abbreviation of suppliers, inputs, process, outputs, and customers. It is a high-level process description without any details. A SIPOC supports the understanding of the process inputs and outputs. It helps to understand the product and information flow from supplier to customer. The process inputs are the needed inputs to the process, like materials, information, and process parameters. The specification for each input can be classified. It can be controllable (C), noise (N), or standard operating procedure (S). Noise inputs are difficult or impossible to control, like environmental conditions. The process outputs are measurable or tangible. They are the result of translating the customer's specifications into measurable specifications. Such a measure is also called a CTQ, and a CTQ tree allows determining the CTQs (CSSC, 2018).

Appendix E Critical to Quality tree lever

The fifth appendix provides the CTQ tree of the lever after translating the VOB into internal CTQs in Figure E.1. Also, it gives a CTQ tree that summarises the data collection plan for process measurement in Figure E.2.

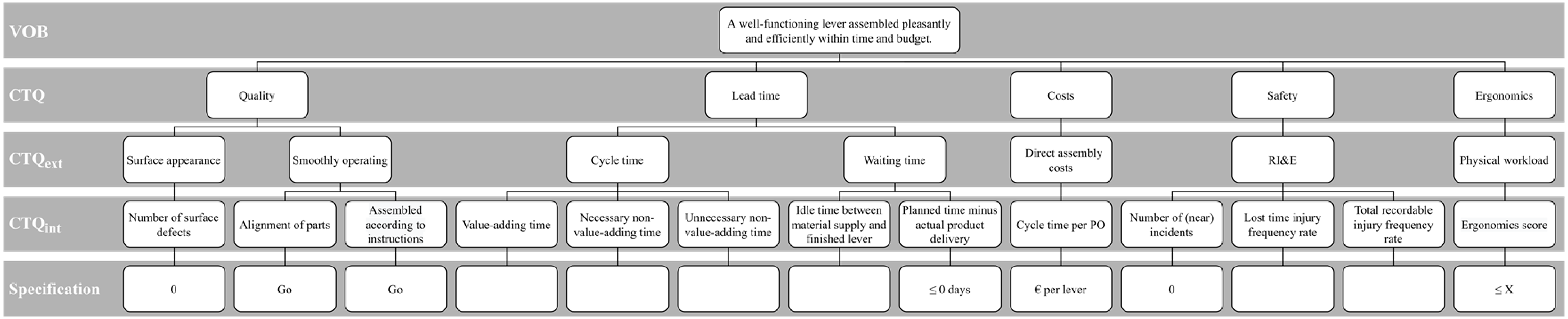


Figure E.1: Critical to quality tree of the lever in the define phase.

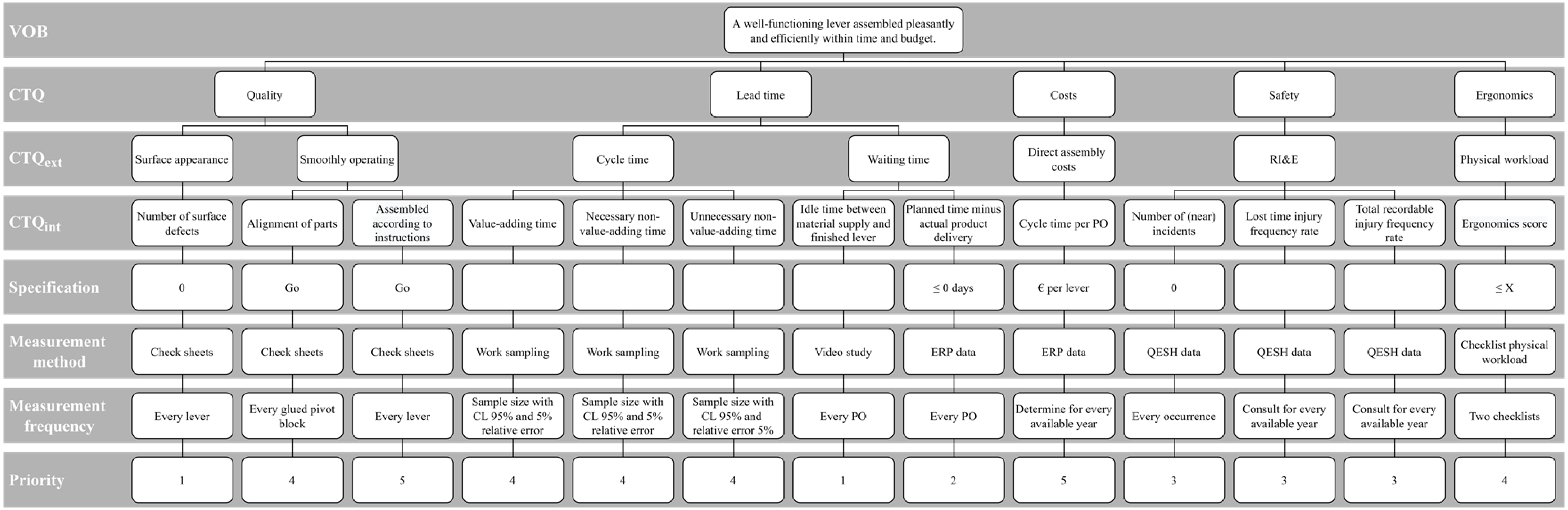


Figure E.2: Critical to quality tree of the lever in the measure phase.

Appendix F Assembly process lever

The assembly of the lever is in five steps, schematically shown in Figure F.1. It starts with glueing bush bearings into the pivot block. Then, the employees press the ball bearings and rolls into the lever in the second and third steps, respectively. Afterwards, they join the lever base to the pivot block. The assembly ends with the mounting of the slide block resulting in a finished lever. After assembly, another employee performs a final check on the finished lever.

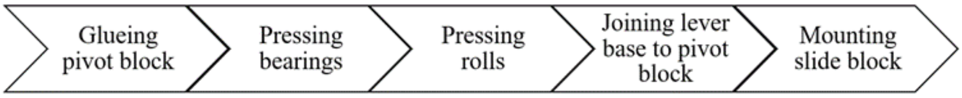


Figure F.1: Schematic overview of the steps in the lever assembly.

Step 1: Glueing of the pivot block

The first step starts by placing the pivot block into a fixture (1) in Figure F.2. Since the fixture can hold the three varieties in pivot blocks, the employees may use a small block to fixate the smaller pivot blocks. Subsequently, the employees place a bush bearing on a metal rod and apply some adhesive (2). Then, they put the bearing on a small metal sheet and slide it till it aligns with the hole in the pivot block (3). Next, by using the metal sheet, rod, and hammer, the employees secure the bush bearing by aligning the flange of the bearing with the surface of the pivot block (4). Afterwards, they remove the excessive adhesive and flip the pivot block. The process repeats, such that on both sides of the pivot block are bush bearings. Finally, the employees use a go or no-go gauge to check whether the bearings align correctly and if the friction is not too high (5). In the case of a no-go, they replace one or two bush bearings and use the gauge once more to check if the pivot block passes inspection.

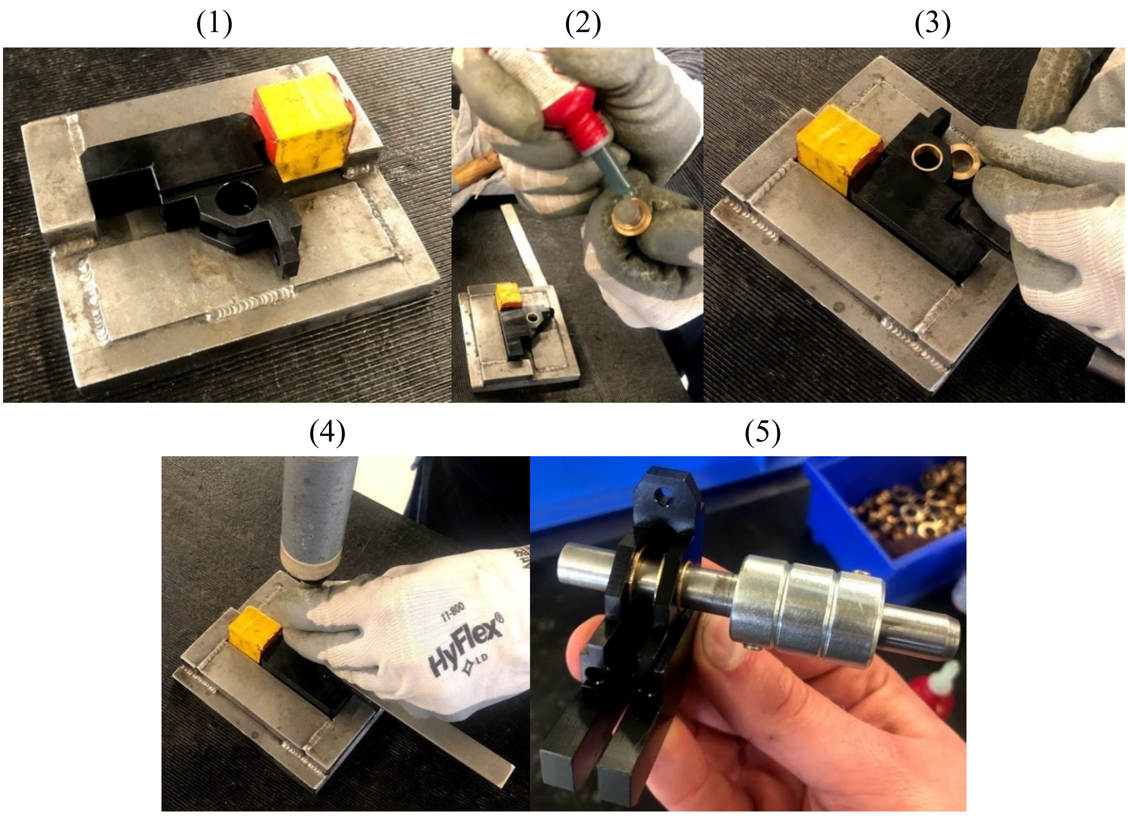


Figure F.2: Glueing of the pivot blocks in steps: placing pivot block into the fixture (1), applying adhesive (2), placing and aligning bush bearing in pivot block (3), securing the bush bearing (4), and quality check with go or no-go gauge (5).

Step 2: Pressing of the bearings

The employees begin the second step by manually pressing a shaft into the lever (1) in Figure F.3. Afterwards, they place a ball bearing on the shaft end. By using the second press, the employees press the bearing entirely onto the shaft (2). Then, they use the third press to flare the shaft end (3). Flaring deforms the shaft end plastically such that it holds the bearing into position. Subsequently, the employees flip the lever and place a shim on the other end of the shaft. They repeat the process, such that on both sides of the shaft are ball bearings. Finally, the employees check for fine cracks in the flare and if the bearings operate smoothly. Rejected levers are put aside and repaired at a later stage.

(1) (2) (3)

Figure F.3: Pressing of the bearings in steps: pressing of a shaft in the lever (1), pressing of a bearing onto the shaft (2), and flaring the shaft end (3).

Step 3: Pressing of the rolls

The pressing of the rolls starts by pre-assembling the rolls. The employees place a roll over the bush and shaft (1) in Figure F.4. Subsequently, they put a shim on top of the roll finishing the pre-assemblies (2). Then, the employees press the finished bush assembly into a lever, already having a set of bearings (3). Afterwards, using the same press, they press the pre-assembled shaft into the bush. The employees continue by flaring the shaft end on a second press (4). Then, they check for fine cracks in the flare and if the rolls operate smoothly. The approved levers, those with bearings and wheels, are called lever bases. The rejected levers are put aside and repaired at a later stage.

(1) (2) (3) (4)

Figure F.4: Pressing of the rolls in steps: placing rolls over the bush and shaft (1), placing a shim on the rolls (2), pressing a pre-assembled shaft on lever (3), and flaring the shaft end (4).

Step 4: Joining the lever base to the pivot block

Joining the lever base to the pivot block uses the same fixture as glueing the bush bearings to the pivot block. After the employees put the pivot block into the fixture, they place a lever base such that it aligns with the bush bearings of the pivot block. Then, they press a dowel by hand through the top bearing to keep the lever base in position (1) in Figure F.5. Afterwards, the employees hammer the dowel into the bottom bush bearing (2). Finally, they swing the lever to check whether it operates smoothly. When it does not run smoothly, the employees adjust the position of the dowel and swing the lever once more.

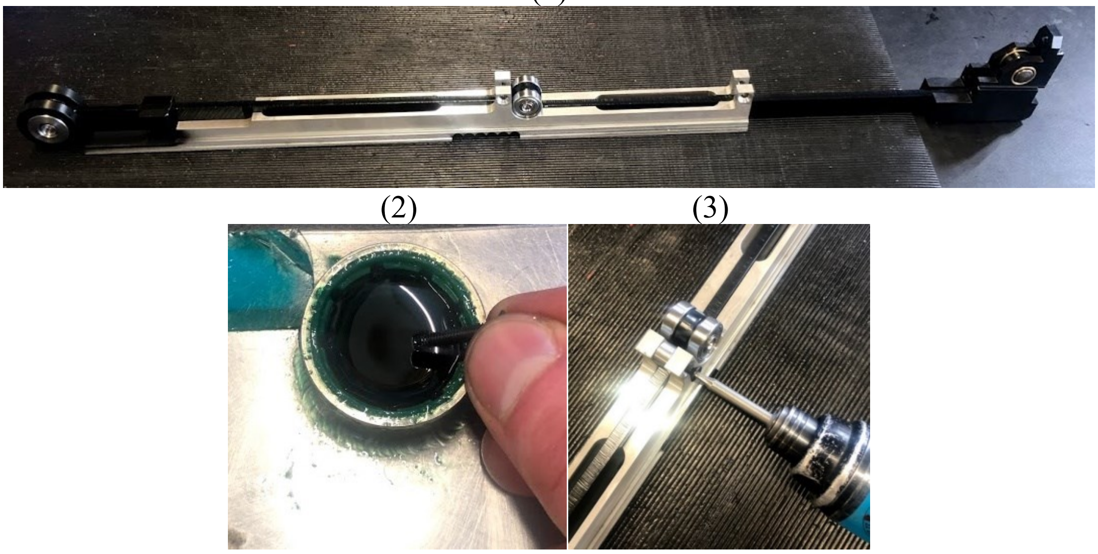
(1) (2)

Figure F.5: Joining the lever base to the pivot block in steps: pressing a dowel through top bearing (1) and hammering the dowel into bottom bush bearing (2).

Step 5: Mounting of the slide block

The employees begin by placing a lever base with a pivot block into an upside-down lying slide block (1) in Figure F.6. Then, they put a spacer in between the slide block. The employees continue by dipping a screw into Loctite (2). Subsequently, they place the screw in the hole of the slide block and through the spacer. The employees tighten the screw slightly and afterwards place the assembly such that it is under tension. Next, they tighten the screw completely with a pneumatic screwdriver (3). The process repeats such that the slide block is connected to the lever base by two screws. Finally, the employee simulates the working condition of the lever by pushing the slide block up. In case it returns to its original position, the lever is approved. In the other cases, the employees tighten the screws once more when the assembly is slightly under tension.

(1)



(2) (3)

Figure F.6: Mounting of the slide block in steps: placing lever base into slide block (1), dipping a screw into Loctite (2), and tighten the screw with pneumatic screwdriver (3).

Final check

The final check is a functional and visual inspection of the finished lever, the four-eyes principle. The employees check the inspection points mentioned in the assembly steps two to five. Afterwards, they pack the levers that passed the inspection into bins. The employees place these bins in an outbound storage location. The levers that do not pass the inspection are put aside for repair or dismantling at a later stage.

Appendix G Incident record sheltered workshop

The seventh appendix provides the incident record of the sheltered workshop over the years in Table G.1. It lists the number of (near) accidents at different levels, the sheltered workshop, per production group, and the lever assembly.

Table G.1: Overview number of (near) incidents over the years at the sheltered workshop subdivided into electrical, mechanical, and lever assembly.

Level		2016	2017	2018	2019	2020
Sheltered workshop	Number of (near) incidents					
Electrical assembly (E763)	Number of (near) incidents					
Mechanical assembly (E720)	Number of (near) incidents					
Lever assembly	Number of (near) incidents					

Appendix H Measurement system analysis

To ensure we collect valid and reliable data, we need to verify that the measurement systems are reliable. Measurement system analysis offers methods to study measurement systems. The following subsections discuss the analyses of the two measurement systems. First, Section H.1 introduces measurement variability. Then, Section H.2 discusses the attribute agreement analysis. Subsequently, Section H.3 and Section H.4 describe the approach and results of applying the attribute agreement analysis to the measurement systems used for the CTQs alignment of parts and assembled according to instructions, respectively.

H.1 Measurement variability

Every production process has variability. The variability observed is the combination of the product and measurement variability, where the product variability is the actual variability. It is essential to minimise the measurement variability to draw reliable conclusions. Theisens (2017) classifies measurement variability into three categories:

1. Accuracy
    a. Bias, the difference between the measured mean and the actual value.
    b. Linearity, the accuracy is equal over the entire measuring range of the measuring instrument.
2. Precision
    a. Repeatability, the variability of the measuring instrument.
    b. Reproducibility, the variability of the measuring procedure.
    c. Uniformity, the degree to which the measurement variation is uniform over the entire measuring range of the measuring instrument.
3. Stability
    a. Time, the stability of the measurement system over time.

A measurement system analysis (MSA) evaluates the measuring instrument and measuring procedure. It provides a statement about the reliability of the measurement system. It can assess quantitative and qualitative data since it has methods for both data types (Theisens, 2017). For the baseline performance, the employees will provide the quality-related data by reporting quality issues. However, determining these quality characteristics objectively is often difficult. For example, the threshold value may differ per employee and measurement instrument. So, we conduct MSAs to evaluate agreement within and between the employees. In this way, we can assess the reliability of the data used as baseline performance.

H.2 Attribute agreement analysis

In the production process of the levers, the used measurement systems concern the internal CTQs alignment of parts and assembled according to instructions. Assessment of these CTQs yields a go or no-go, which is qualitative data. An attribute agreement analysis can evaluate qualitative data, also called attributive data. It requires two or more appraisers independently assess at least 20 parts, in a random order, at least two times. The method evaluates the ability of the appraisers to agree with themselves (repeatability), with each other (reproducibility), and with a known standard (accuracy). The attribute agreement analysis produces statistics, generally expressed in a kappa value (CSSC, 2018). Kappa is the ratio of the proportion of times that the appraisers agree (corrected for chance agreement) to the maximum proportion of times that the appraisers could agree (corrected for chance agreement). The kappa values range from -1 to +1, and the higher the value, the stronger the agreement. A kappa value of 1 means the appraisers agree perfectly, while a value of 0 means agreement is the same as would be expected by chance. A negative kappa value means the appraisers agree less than expected by chance. The Automotive Industry Action Group suggests that a kappa value of at least 0.75 indicates good agreement. However, larger kappa values, such as 0.90, are preferred (Minitab, 2019).

To perform the attribute agreement analyses, we use Minitab. It has tools to create and evaluate an attribute agreement analysis. It generates based on the number of appraisers, replications, and samples a worksheet. The worksheet places the numbered samples in a random run order. The analysis returns a kappa value for repeatability, reproducibility, and accuracy. As a threshold value for good agreement, we use 0.75, as previously suggested.

H.3 Alignment of parts

The alignment of parts refers to the bush bearings in the pivot block. The employees use a go or no-go gauge to check if the bearings align correctly and if the friction is not too high. They assess whether the part passes since a value that limits the maximum friction is absent. Furthermore, they can use multiple go or no-go gauges for the assessment, of which the characteristics vary per gauge. To overcome the latter issue, we used the most recently purchased go or no-go gauge. To define the known standard and overcome the first issue, we grouped glued pivot blocks by friction. The five groups ranged from smooth to rather heavy. In agreement with a multidisciplinary team, we assessed the first three groups as passes. We compiled a mix of these five groups, where 20 parts met the specifications and ten did not. We did not number the parts. Only noted the location of the randomly placed faulty parts at the start of the first assessment. In this way, the pivot blocks get assigned to a traceable number, and we minimise the ability of the appraisers to remember their previous results. Figure H.1 shows the arrangement of the pivot blocks for the attribute agreement analysis of the pivot blocks. Three employees independently assessed the 30 parts twice. Between the assessments of every 30 pivot blocks, we exchanged the parts as suggested by the generated run order.

Figure H.1: Pivot block arrangement for the attribute agreement analysis.

The attribute agreement analysis in Minitab returns a kappa value for repeatability, reproducibility, and accuracy. The analysis results in the following findings:

The graphical output of Minitab, given in Figure H.2, returns the agreement within the appraisers, the repeatability. Furthermore, it shows the agreement between appraisers and the standard: the accuracy. The dots represent the actual agreement for each appraiser. The crosses are the bounds of a 95% confidence interval of the expected performance of each appraiser. The confidence intervals of the expected performance compared to the known standard of appraisers . They are the result of the kappa value. The attribute agreement analysis shows that the employees need additional training. Also, the need for standardisation of the procedure and go or no-go gauges. Finally, the analysis reveals that we should critically assess this part of the baseline performance. It may not be reliable.

Table H.1: Repeatability within appraisers.

Appraiser	# Inspected	# Matched	Kappa
1	30		
2	30		
3	30		

Matched: Appraiser agrees with him/herself across trials.

Table H.2: Accuracy of each appraiser versus the standard.

Appraiser	# Inspected	# Matched	Kappa
1	30		
2	30		
3	30		

Matched: Appraiser's assessment across trials agrees with the known standard.

Table H.3: Disagreement appraisers versus the standard.

Appraiser	# No-Go/Go	# Go/No-Go	# Mixed
1			
2			
3			

No-Go/Go: Assessments across trials no-go, known standard go.
Go/No-Go: Assessments across trials go, known standard no-go.
Mixed: Assessment across trials are not identical.

Table H.4: Reproducibility between appraisers.

# Inspected	# Matched	Kappa
30		

Matched: All appraisers' assessments agree with each other.

Table H.5: Accuracy of all appraisers versus the standard.

# Inspected	# Matched	Kappa
30		

Matched: All appraisers' assessments agree with the known standard.

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Figure H.2: Repeatability within appraisers (l) and accuracy of each appraiser versus the standard (r).

H.4 Assembled according to instructions

Assembled according to instructions refers to the final check of a finished lever. The employees perform a functional and visual inspection to check assembled levers of another employee. The employees inspect the following points:

- Bearings operating smoothly and flared without fine cracks.
- Rolls operating smoothly and flared without fine cracks.
- The lever base is aligned properly and rotates smoothly in the pivot block.
- Slide block moving up and down easily.

We compiled a sample of 30 levers, of which 20 finished levers were conforming products and ten non-conforming products. The ten faulty products consisted of levers with seized bearings and rolls, flares with fine cracks, improperly aligned lever bases, and non-returning slide blocks. As with the alignment of parts, we did not number the parts to minimise the ability of the appraisers to remember their previous results. We only noted the locations of the faulty products at the start of the first assessment to trace them throughout the test. Figure H.3 shows the arrangement of the levers for the attribute agreement analysis of the pivot blocks. Three employees independently assessed the 30 parts twice. Between the assessments of every 30 pivot blocks, we exchanged the parts as suggested by the generated run order.

Figure H.3: Lever arrangement for the attribute agreement analysis.

The attribute agreement analysis results in the following findings:

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Figure H.4 shows the graphical output of the attribute agreement analysis. It gives the agreement within the appraisers, the repeatability, and the agreement between appraisers and the standard, the accuracy. The confidence intervals of the expected performance compared to the known standard . The kappa value for each appraiser versus the known standard results in intervals. The analysis reveals that the employees need additional training for the new production process design. Also, it reveals the need for clear quality standards and the standardisation of the procedure. Finally, we should also critically evaluate this part of the baseline performance. It also may not be as reliable.

Table H.6: Repeatability within appraisers.

Appraiser	# Inspected	# Matched	Kappa
1	30		
2	30		
3	30		

Matched: Appraiser agrees with him/herself across trials.

Table H.7: Accuracy of each appraiser versus the standard.

Appraiser	# Inspected	# Matched	Kappa
1	30		
2	30		
3	30		

Matched: Appraiser's assessment across trials agrees with the known standard.

Table H.8: Disagreement appraisers versus the standard.

Appraiser	# No-Go/Go	# Go/No-Go	# Mixed
1			
2			
3			

No-Go/Go: Assessments across trials no-go, known standard go.
Go/No-Go: Assessments across trials go, known standard no-go.
Mixed: Assessment across trials are not identical.

Table H.9: Reproducibility between appraisers.

# Inspected	# Matched	Kappa
30		

Matched: All appraisers' assessments agree with each other.

Table H.10: Accuracy of all appraisers versus the standard.

# Inspected	# Matched	Kappa
30		

Matched: All appraisers' assessments agree with the known standard.

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Figure H.4: Repeatability within appraisers (l) and accuracy of each appraiser versus the standard (r).

Appendix I Distribution identification

The ninth appendix presents the outcomes of fitting the assembly time of the lever to 14 probability distributions and one data transformation in Figure I.1. Moreover, it depicts the probability plots of fitting the same data to the probability distributions exponential, gamma, lognormal and Weibull in Figure I.2.

Distribution	AD	P	LRT P
Normal	4,281	<0,005	
Box-Cox Transformation	3,250	<0,005	
Lognormal	22,537	<0,005	
3-Parameter Lognormal	3,767	*	0,000
Exponential	119,972	<0,003	
2-Parameter Exponential	83,024	<0,010	0,000
Weibull	2,817	<0,010	
3-Parameter Weibull	3,614	<0,005	0,176
Smallest Extreme Value	22,169	<0,010	
Largest Extreme Value	7,030	<0,010	
Gamma	9,111	<0,005	
3-Parameter Gamma	4,411	*	0,000
Logistic	5,091	<0,005	
Loglogistic	16,859	<0,005	
3-Parameter Loglogistic	5,256	*	0,000

Figure I.1: Goodness of fit test of the assembly time per lever against 14 probability distributions and one data transformation.

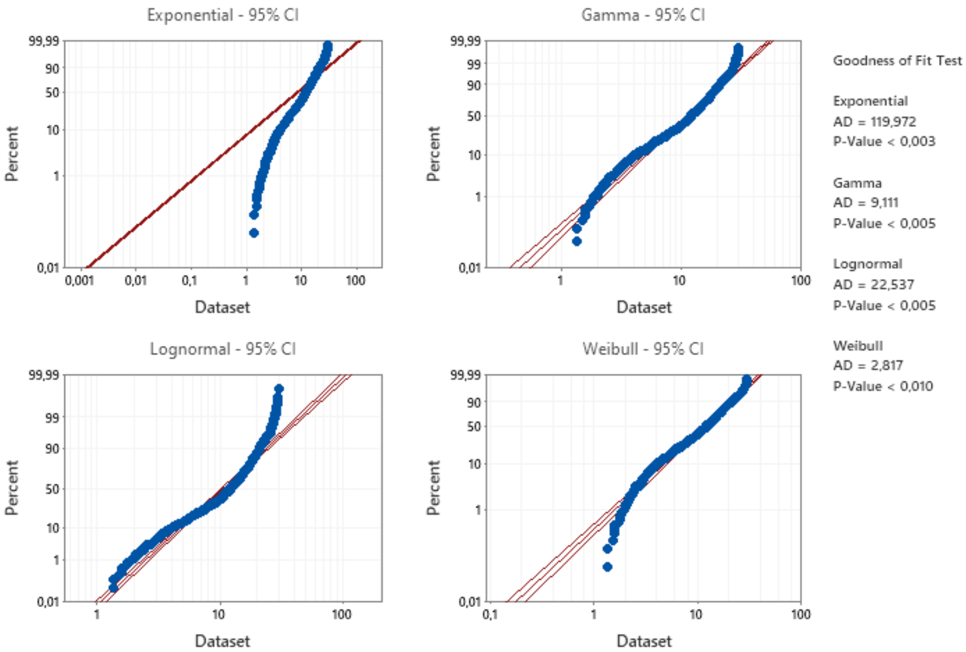

Figure I.2: Probability plots and goodness of fit tests of exponential, gamma, lognormal, and Weibull distribution.

Appendix J Spaghetti diagrams

The performance analysis in Chapter 4 used spaghetti diagrams to determine the efficiency of the facility layout per assembly step. The diagrams are in Figure J.1 to Figure J.5.

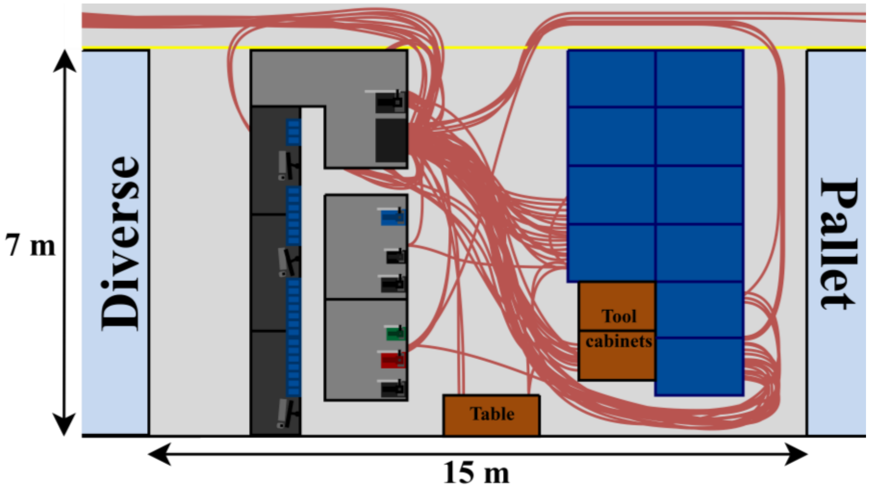

Figure J.1: Spaghetti diagram of the first assembly step: glueing of the bush bearings into the pivot block.

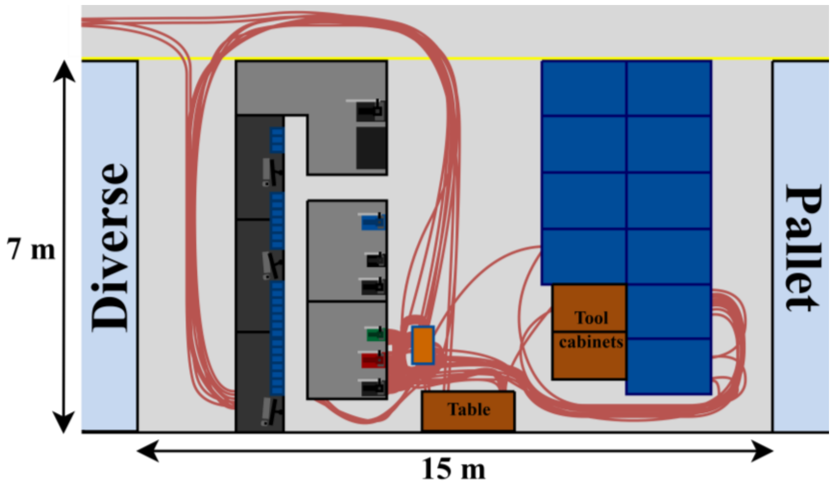

Figure J.2: Spaghetti diagram of the second assembly step: pressing of the bearings.

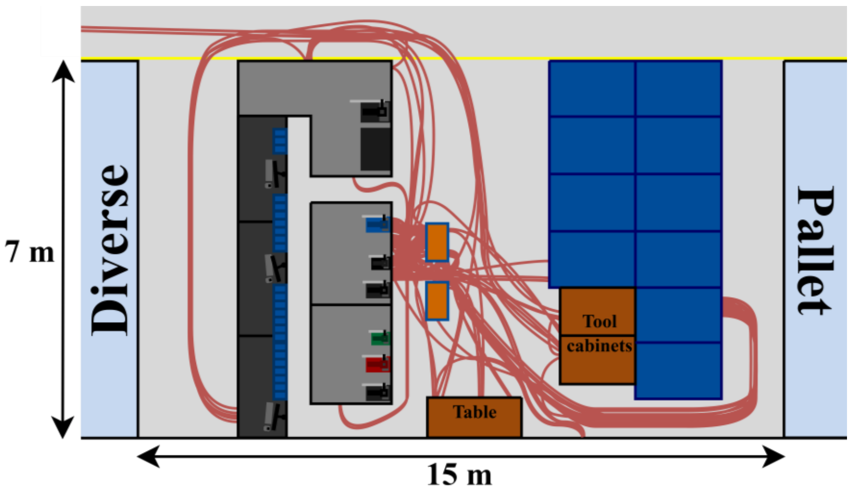

Figure J.3: Spaghetti diagram of the third assembly step: pressing of the rolls.

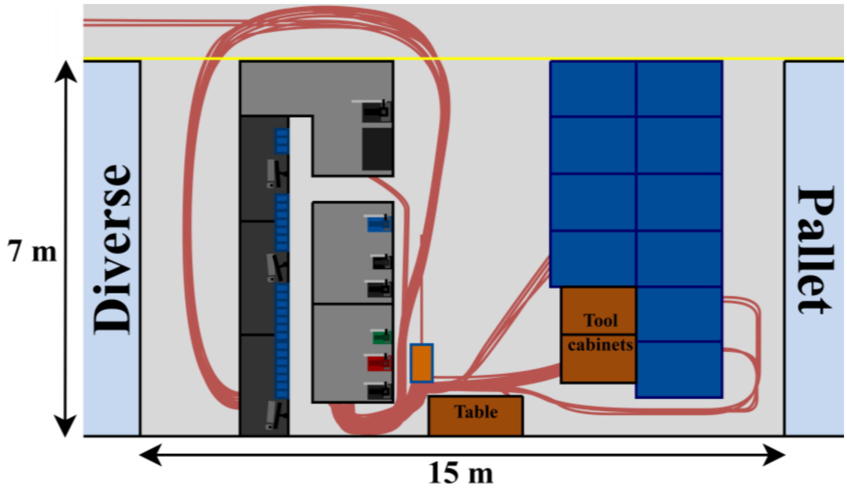

Figure J.4: Spaghetti diagram of the fourth assembly step: joining the lever base to the pivot block.

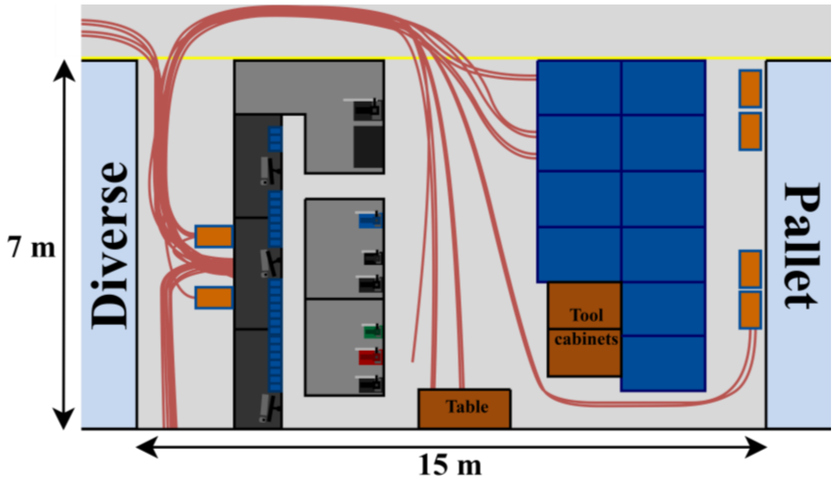

Figure J.5: Spaghetti diagram of the fifth assembly step: mounting of the slide block.

Appendix K Swimlanes

In the performance analysis of Chapter 4, we use swimlanes to visualise processes and identify the responsibilities of actors. We based the findings on the material supply, lever repair, PO prioritisation, and every assembly step on the swimlanes in Figure K.1 to Figure K.7.

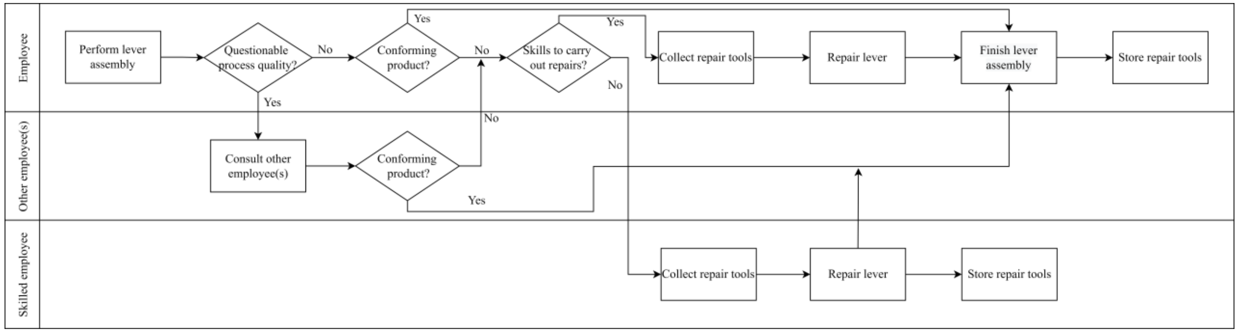

Figure K.1: Swimlane of the repair process during lever assembly.

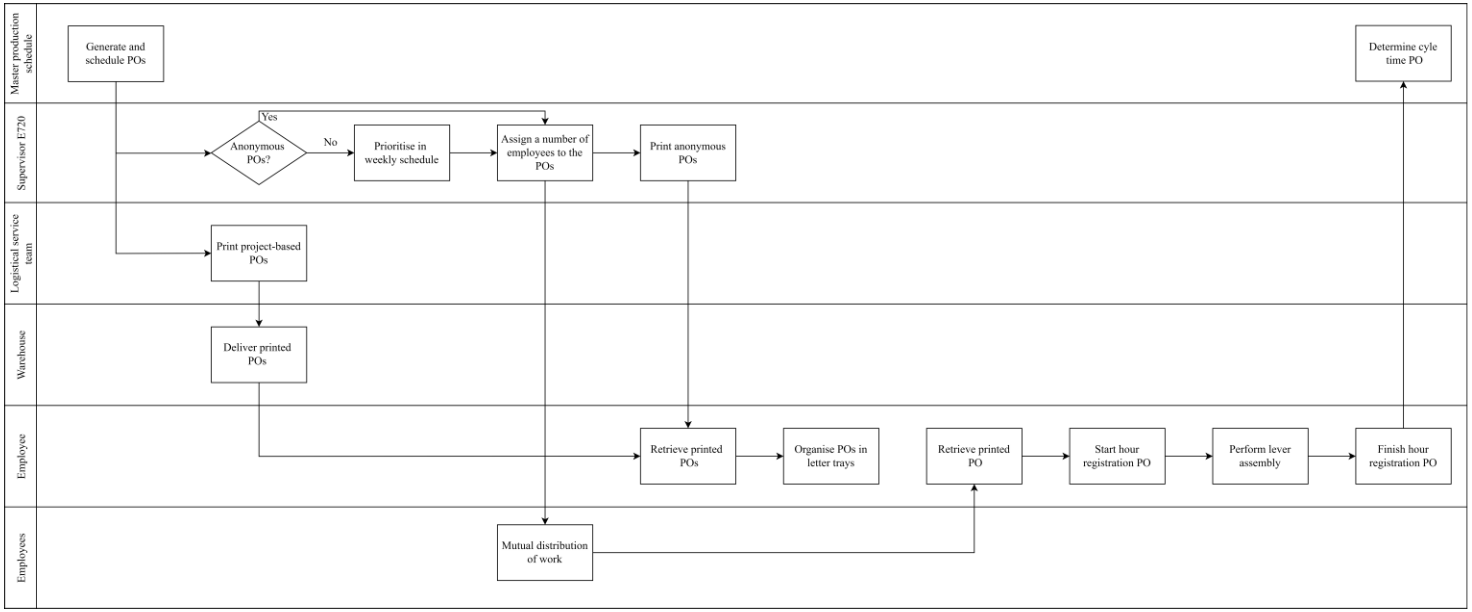

Figure K.2: Swimlane of PO prioritisation and distribution.

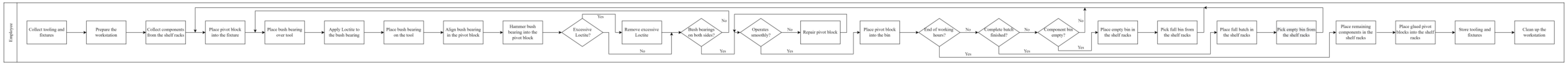

Figure K.3: Swimlane of the first assembly step: glueing the pivot blocks.

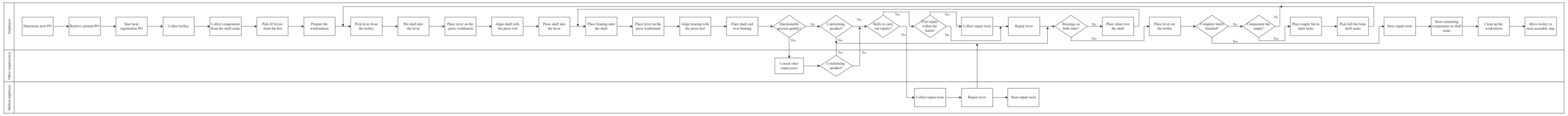

Figure K.4: Swimlane of the second assembly step: pressing the bearings.

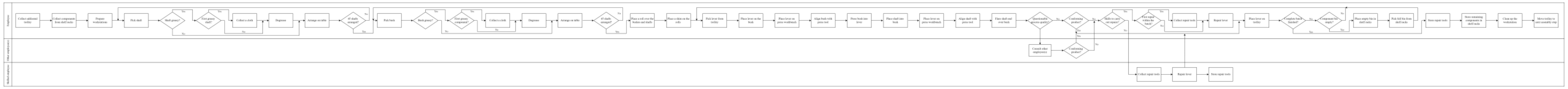

Figure K.5: Swimlane of the third assembly step: pressing the rolls.

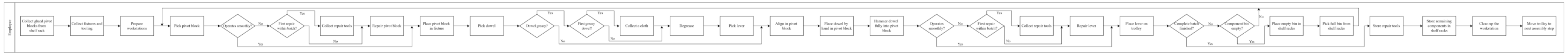

Figure K.6: Swimlane of the fourth assembly step: joining the lever base to the pivot block.

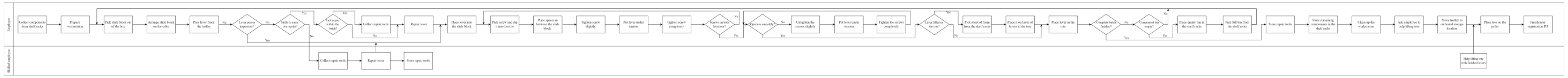

Figure K.7: Swimlane of the fifth assembly step: mounting the slide block.

Appendix L Cause and effect diagram

The brainstorming session identified 26 causes and 66 subcauses, over the categories machines, methods, materials, manpower, measurement, and environment, why the VA percentage is only %. Figure L.1 shows all these causes in the extended version of the fishbone diagram.

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Figure L.1: Fishbone diagram of causes influencing the VA percentage (extended version).

Appendix M Cause and effect matrix

In Chapter 4, we asked a multidisciplinary team to score the correlation between the key input variables and the key output variables. After a discussion the multidisciplinary team agreed on the correlation scores given in Table M.1.

Table M.1: Cause and effect matrix scoring the correlation between the key input variables and the key output variables.

Cause & Effect Matrix

		Rating Customer Importance : →	4	5	4	4	4	5	4	
			2	3	4	5	6	9	13	
Rating: 0 - no effect 1 - weak effect 3 - moderate effect 9 - strong effect		KPOV : → Key Process Output Variables (Customer requirements)	Alignment of parts	Assembled according to instructions	Value-adding time	Necessary non-value-adding time	Unnecessary non-value-adding time	Cycle time per PO	Ergonomics score	Total
	Process Step	KPIV: ↓ Key Process Input Variables								
1	Materials	*Confidential*	0	0	9	9	1	9	3	**133**
2			9	9	9	0	9	9	0	**198**
3			0	0	9	9	0	9	0	**117**
4			0	0	9	9	3	9	1	**133**
5			0	0	3	3	0	1	9	**65**
6	Manpower		1	1	3	3	9	3	0	**84**
7			0	0	3	3	0	1	1	**33**
8			1	1	1	1	3	1	9	**70**
9			3	9	3	3	3	3	3	**120**
10			0	0	1	1	1	1	9	**53**
11	Environment		0	0	3	1	1	1	3	**37**
12			1	1	3	1	1	1	0	**34**
13			0	0	3	3	9	3	1	**79**
14	Methods		0	0	9	9	9	9	3	**165**
15			0	0	9	0	9	9	3	**129**
16			9	9	9	3	3	9	0	**186**
17			0	0	3	3	3	3	0	**51**
18	Machines		0	9	3	3	9	3	0	**120**
19			3	9	3	3	3	3	3	**120**
20			3	1	9	9	3	9	3	**158**
21			1	1	3	3	1	3	0	**52**
22			0	9	9	3	9	3	3	**156**
23	Measurement		0	0	3	3	0	3	0	**39**
24			9	9	9	3	9	9	0	**210**
25			9	3	1	3	9	3	0	**118**
26			3	3	1	1	3	3	0	**62**
Total :			**208**	**370**	**520**	**368**	**440**	**600**	**216**	

Appendix N Interrelationship diagram

The interrelationship diagram depicts the relationships among the influence factors in the complex problem situation of the lever in Figure N.1.

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Figure N.1: Interrelationships diagram of the cause and effect matrix (extended version).

Appendix O Changes in assembly methods and product design

The current lever assembly process consists of two parallel processes, whereas the literature indicates that a one-piece flow process is an ideal production process. Fortunately, we see opportunities to merge the two parallel processes into one process. Therefore, we suggest a new assembly method that presses the bush bearings into the pivot block instead of using an adhesive in Section O.1. Furthermore, we present a new assembly method to join the lever base to the pivot block in Section O.2. Then, we elaborate on two design changes to the slide blocks in Section O.3.

O.1 Pressing bush bearings into the pivot block

The new assembly method presses the bush bearings into the pivot block, depicted in Figure O.1. The design of bush bearings allows pressing them into the housing bore, and thus Engineering agreed on testing the new assembly method. Implementing this assembly method replaces the three steps currently needed to assemble a pivot block. The ultrasonic cleaning, to ensure adhesion, and the curing time of at least six hours become redundant. The latter allows merging the two parallel processes into a one-piece-flow process. Furthermore, it reduces the workload of the assembly step, hence reducing the assembly time. The new assembly method also simplifies the tasks for the employees. In addition, the use of the adhesive and the ultrasonic fluid become redundant. They are hazardous substances. They irritate the eyes, skin, and respiratory passages. Moreover, the fumes of the adhesive are carcinogenic in case of prolonged exposure.

. The elimination of these hazardous substances ensures safe working conditions, a fixed requirement in subsection 6.1.2. The final advantage is a reduction in walking distances of 300 meters per trip to the fume extractor. So, pressing the bush bearings into the pivot block reduces assembly time, improves the health and safety of the employees, and allows the lever assembly to be a one-piece-flow process.

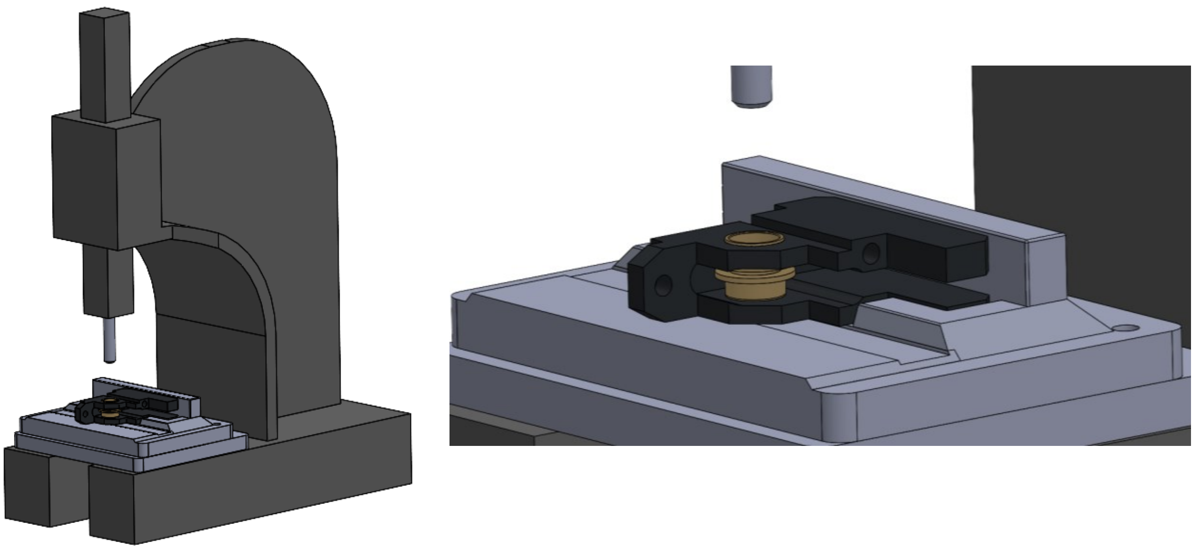


Figure O.1: New assembly method to press the bush bearings into the pivot block.

O.2 Pressing dowel to join lever base to the pivot block

The second new assembly method replaces the fourth assembly step in the current process. It is the assembly step where % of the performed repairs in the baseline performance originate. The new method joins the lever base to the pivot block using a press instead of hammering, as Figure O.2 visualises. The first advantage is that it presses the dowel into position in one stroke, reducing assembly time. Moreover, it currently is a delicate step requiring a lot of training and experience. Finally, it improves working conditions, there is no more hammering noise, and the employees do not need to use force to align the lever base and pivot block by hand. The new assembly method ensures safe working conditions, a fixed requirement, and likely improves the process quality, a variable requirement. After presenting the new assembly method to Engineering, they approved it for testing. Summarised, pressing the dowel into the pivot block using a press reduces assembly time, improves working conditions, and eases the assembly.

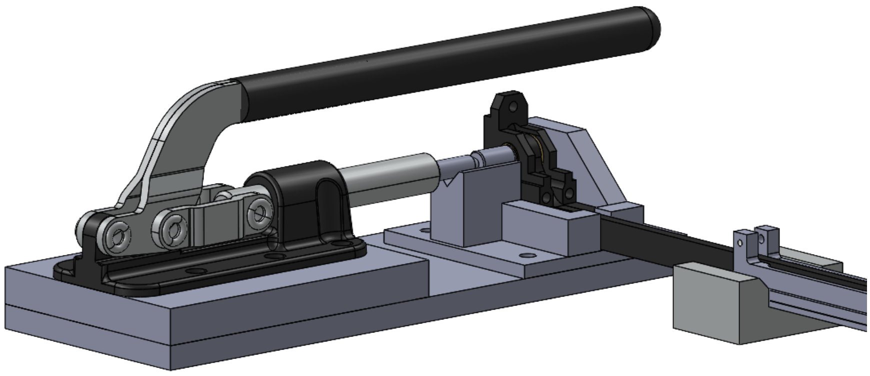


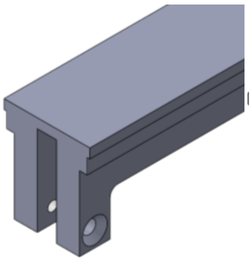
Figure O.2: New assembly method to join the lever base to the pivot block by pressing the dowel into the pivot block.

O.3 Design change of slide blocks

Although design changes are not within the research scope, they constitute a great opportunity. So let us briefly discuss them. The design change of the slide blocks eliminates about half of the current workload at the final assembly step. It allows to 'scoop' the lever into the slide block. Hence, a screw and spacer become redundant. Furthermore, we recommend replacing the remaining screw, which the employees dip into adhesive, with a tuflok screw. Tuflok screws have a small spot with a nylon coating, illustrated in Figure O.3. When fastened, the nylon coating compresses and retains the screw in place. Tuflok screws have several advantages (e.g., reusable and immediate securing), but most importantly, it is not hazardous. It eliminates the use of the adhesive, ensuring safe working conditions, which is a fixed process requirement. The price of a tuflok screw is two cents higher. However, the eliminated adhesive and minor cycle time reduction compensate for the higher price. Even if there is a minor financial loss, it does not outweigh the gain in safety. Engineering agreed with this view and approved ordering a test sample for further examination. Hence, several activities should be carried out before implementation, mentioned in more detail in the implementation plan in subsection 8.1.3.

Figure O.3: Tuflok screw, where the blue spot is the nylon coating (Kerbkonus, n.d.).

Scooping the lever into the slide block is only possible if the lever has not joined the pivot block. Thus, the fourth and fifth assembly steps swap positions in the new assembly sequence, which we list at the end of this subsection. The employees first mount the slide block and afterwards join the lever base to the pivot block. Engineering approved further detailing of the slide block design in consultation with the supplier. It resulted in the design given in the second picture of Figure O.4. The figure also shows the current design in the first picture and the intended assembly method in the third picture. The component price is equal to the current price. Therefore, it means that it financially is a viable design. However, before implementing the design change, we first need to determine if it is technically feasible. Subsection 8.1.3 describes the procedure to follow to demonstrate the technical feasibility of the design.



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(1) (2) (3)

Figure O.4: Design change of the slide block, current design (1), design proposal (2), and intended assembly method (3).

So, the new design of the slide block and use of tuflok screws reduce the assembly time and component costs, improve the working conditions, change the assembly sequence, and are financially viable. However, the design changes of the slide block may not be technically feasible.

Appendix P Process layout evaluation

The flow the materials follow in the new process design is the line flow, discussed in subsection 6.2.2. However, we left which variant of the line flow (e.g., I-flow, O-flow, or U-flow) open. By determining the production control strategy, the assembly sequence, and the tooling, we can start outlining potential layouts of the process. For this purpose, we study variants where the materials follow an I-flow, L-flow, O-flow, and U-flow. Figure P.1 gives an impression of the different layouts. The centre-to-centre distance between the workstations is 0.7 meters, slightly smaller than the human average step length (Frothingham, 2018). A shorter distance leaves too little room for the employees to manoeuvre side by side with ease and a larger distance only adds additional wasteful meters. Evaluation of the layout variants uses the criteria communication and overview, line balancing, and walking distance.

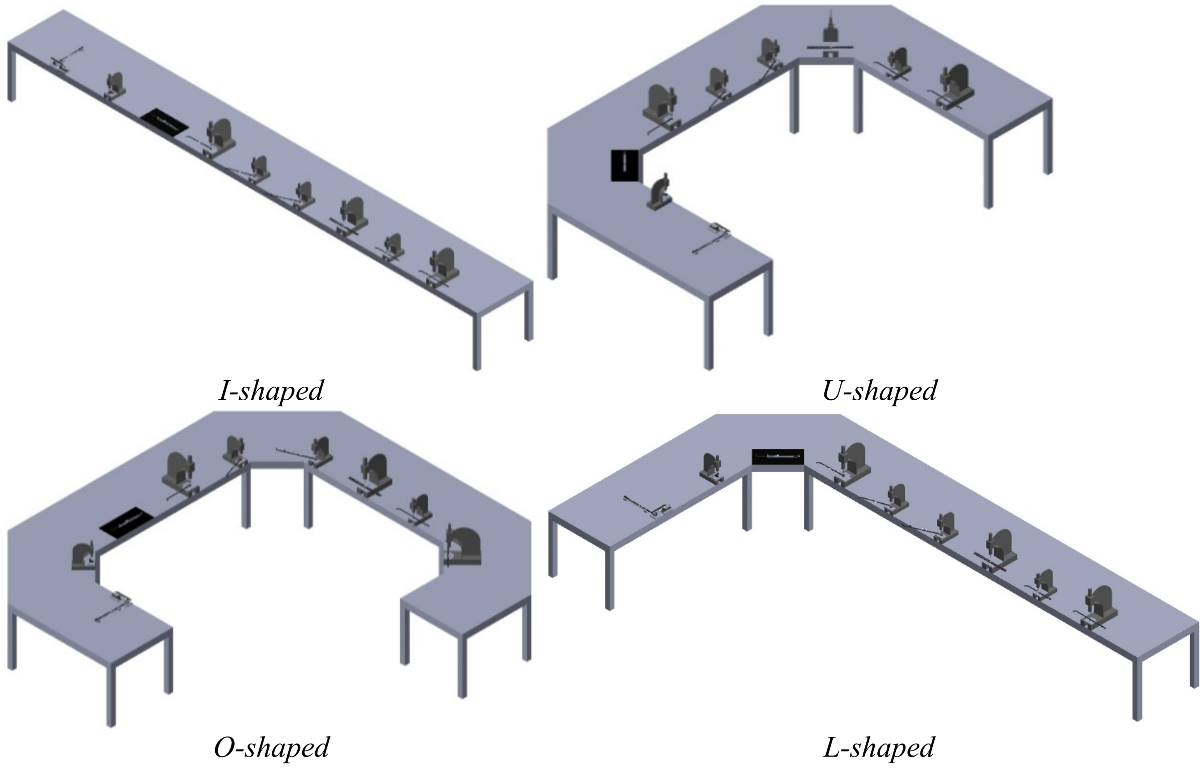

Figure P.1: Visualisation of the levers assembly in an I-shaped, L-shaped, O-shaped, and U-shaped layout.

Communication and overview

Communication and overview between employees are important aspects of an assembly process (MANTEC, 2019). Effective communication in a noisy factory without leaving workstations means that the distance between employees should not be too great. Close arrangement of the workstations is convenient to inform colleagues of quality issues or to keep an overview of what is happening in the process. Hence, the distance between the two most distant workstations should be as small as possible. This distance is the largest for the straight-line layout, and the L-shaped layout follows next. The O-shaped and U-shaped layouts have alike distances, as the second column of Table P.1 gives. Thus, the O-shaped and U-shaped layouts best suit the lever assembly for effective communication and a good overview.

Line balancing

The second criterion evaluates the opportunities for line balancing. Line balancing is important to smoothen the production flow and cope with variability in workload (Jameel, 2015). For this purpose, we determine the number of neighbouring workstations over which we can potentially balance the workload. The third column of Table P.1 specifies this number. It lists that the O-shaped and U-shaped layouts best suit workload balancing. It also counts the workstations on the opposite side of the process as balancing potential. The balancing options for the I-shaped and L-shaped are limited. So, the O-shaped and U-shaped layouts are more appropriate for line balancing.

Walking distance

The walking distance represents the distance employees would have walked if they assembled one lever. Reducing the walking distance to a minimum is essential. One reason is that the variability in demand can result in only one employee assembling levers. Moreover, an alternative to line balancing is that the employees follow each other in the process. In that case, the employees fully assemble a lever. Therefore, just a few redundant meters combined with the annual demand of levers wastes a lot of time in motion. The fourth and fifth column of Table P.1 gives the distance employees walk during assembly and the distance from the last to the first workstation. It shows that employees would walk as many meters during assembly as walking back to the first workstation with an I-shaped layout. The O-shaped and U-shaped layouts have almost similar walking distances and are the shortest. Finally, the walking distance of the L-shaped layout is in between the others. In short, the layouts with the shortest walking distance are O-shaped and U-shaped.

Table P.1: Assessment scores of the different layout variants on the aspects of communication and overview, floor area, line balancing, and walking distance.

Layout variant	Distance most distant workstations [m]	Number of neighbouring workstations	Walking distance [m]		
			Assembly	Final to first workstation	Total
I-shaped	7.0	1-2	7.0	7.0	14.0
L-shaped	5.5	1-2	6.7	5.5	12.3
O-shaped	4.0	4-6	6.7	3.8	10.5
U-shaped	3.6	4-6	6.5	3.5	10.0

Layout exclusion

The first evaluation of the potential layout variants justifies excluding the I-shaped and L-shaped layouts. Their arrangement of the workstations is not close enough for effective communication and overview. Furthermore, their potential for line balancing is limited due to the limited number of neighbouring workstations. Lastly, the distance employees would walk to assemble one lever far exceeds the walking distance at the O-shaped and U-shaped layout. The latter two have alike scores in communication and overview, line balancing, and walking distances. Therefore, after further detailing the process design, we evaluate the two remaining layout variants once more on the required floor area, safety, and integration of material supply.

Appendix Q ERP data lever POs

The standard inventory of lever and slide blocks was determined using the annual production quantity per lever variety, given in Table Q.1 and Table Q.2, and the number of annual POs per lever variety, listed in Table Q.3. When VMI desires higher volume fill rates or fill rates, Table Q.4 and Table Q.5 define the additional levers and slide blocks that become standard inventory.

Table Q.1: Annual production quantity per lever variety over the years.

Lever variety	2016	2017	2018	2019	2020	Average
12"-13"-L398.5						
12"-13"-L398.5 (M)						
12"-13"-L398.5 (V)						
14"-17"-L395						
14"-17"-L395 (M)						
14"-17"-L395 (V)						
14"-18"-L495						
14"-18"-L495 (M)						
14"-18"-L495 (V)						
16"-18"-L395						
16"-18"-L395 (M)						
16"-18"-L395 (V)						
19"-20"-L413						
19"-20"-L413 (M)						
19"-20"-L413 (V)						
19"-24"-L493						
19"-24"-L493 (M)						
19"-24"-L493 (V)						

Table Q.2: Annual production quantity share per lever variety over the years.

Lever variety	2016	2017	2018	2019	2020	Average
12"-13"-L398.5						
12"-13"-L398.5 (M)						
12"-13"-L398.5 (V)						
14"-17"-L395						
14"-17"-L395 (M)						
14"-17"-L395 (V)						
14"-18"-L495						
14"-18"-L495 (M)						
14"-18"-L495 (V)						
16"-18"-L395						
16"-18"-L395 (M)						
16"-18"-L395 (V)						
19"-20"-L413						
19"-20"-L413 (M)						
19"-20"-L413 (V)						
19"-24"-L493						
19"-24"-L493 (M)						
19"-24"-L493 (V)						

Table Q.3: Annual number of POs per lever variety over the years.

Lever variety	2016	2017	2018	2019	2020	Average
12"-13"-L398.5						
12"-13"-L398.5 (M)						
12"-13"-L398.5 (V)						
14"-17"-L395						
14"-17"-L395 (M)						
14"-17"-L395 (V)						
14"-18"-L495						
14"-18"-L495 (M)						
14"-18"-L495 (V)						
16"-18"-L395						
16"-18"-L395 (M)						
16"-18"-L395 (V)						
19"-20"-L413						
19"-20"-L413 (M)						
19"-20"-L413 (V)						
19"-24"-L493						
19"-24"-L493 (M)						
19"-24"-L493 (V)						

Table Q.4: Levers and slide blocks required in inventory to achieve the volume fill rate targets.

Volume fill rate	Lever varieties	
%	14"-18"-L495 14"-18"-L495 (M)	19"-24"-L493 19"-24"-L493 (M)
Target volume fill rate	**Additional required lever varieties**	
%		
%		
%		

Table Q.5: Levers and slide blocks required in inventory to achieve the fill rate targets.

Fill rate	Lever varieties	
%	14"-18"-L495 14"-18"-L495 (M)	19"-24"-L493 19"-24"-L493 (M)
Target fill rate	**Additional required lever varieties**	
%		
%		
%		

Appendix R Fixtures lever assembly

In the workstation design in Chapter 6, we designed new fixtures and pressing tools. Section R.1 gives an overview of all the designed fixtures. Afterward Section R.2 provides an overview of the pressing tools.

R.1 Fixtures lever assembly

Figure R.1 to Figure R.8 present the fixtures for the lever range 14”-18” for the new process design of the lever.

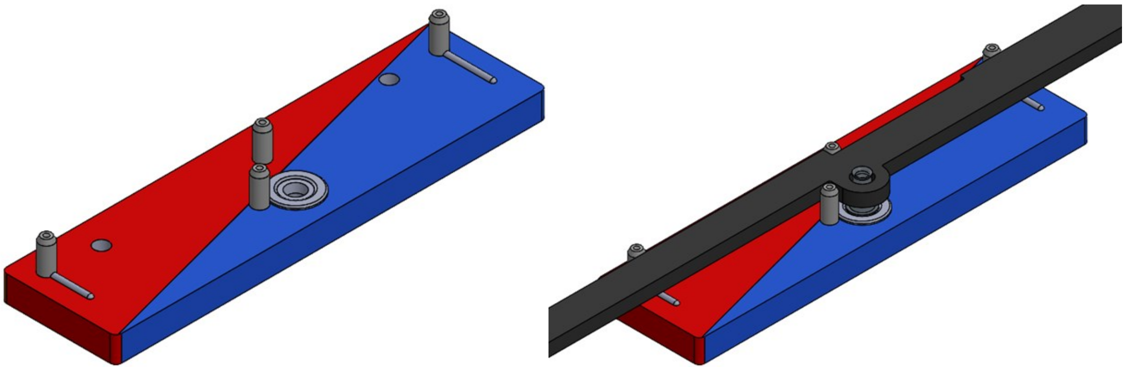

Figure R.1: Fixture for pressing the shaft for the ball bearings into the lever, lever range 12”-18” with (r) and without the components (l).

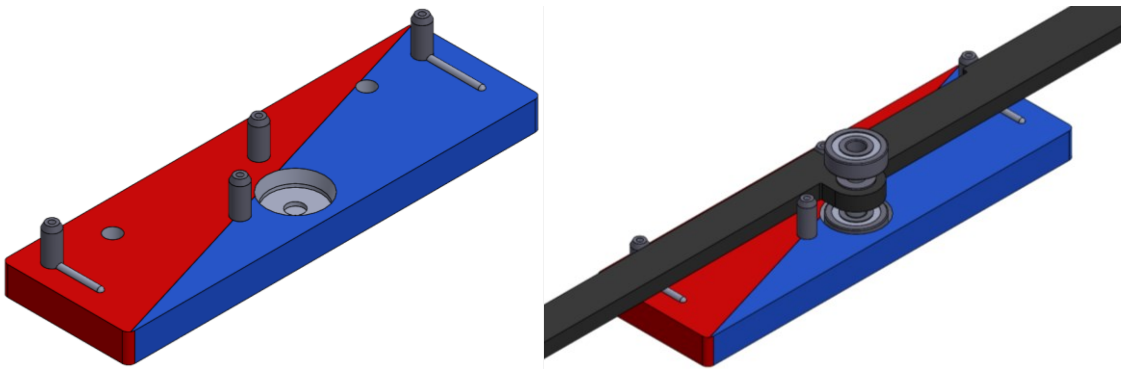

Figure R.2: Fixture for pressing the ball bearings onto the shaft, lever range 12”-18” with (r) and without the components (l).

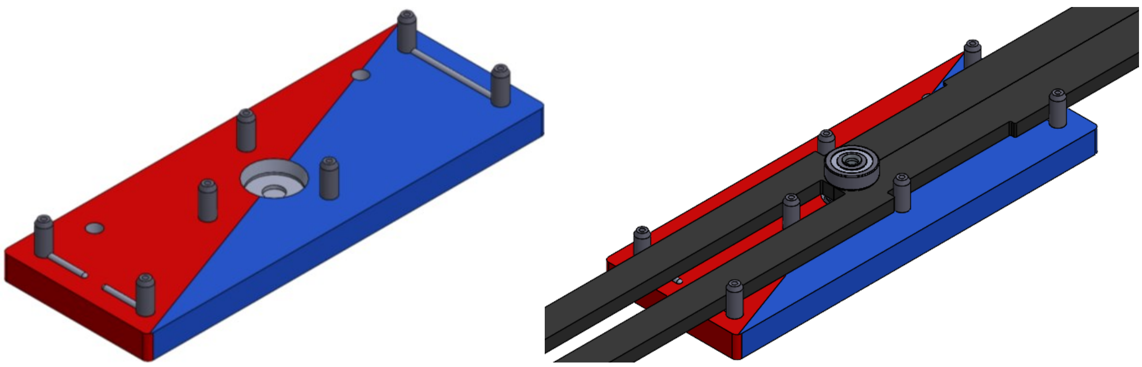

Figure R.3: Fixture for flaring the shaft of the ball bearings, lever range 12”-18” with (r) and without the components (l).

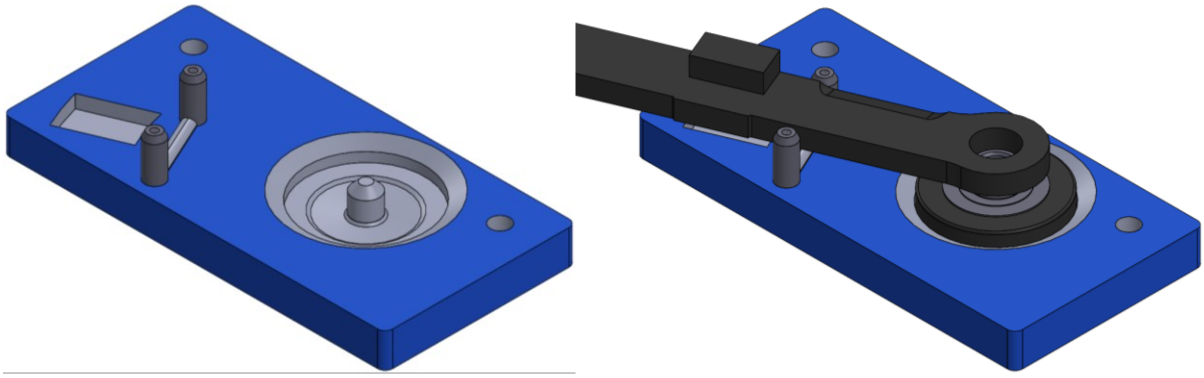

Figure R.4: Fixture for pressing the bush with a roll into the lever, lever range 14”-18” with (r) and without the components (l).

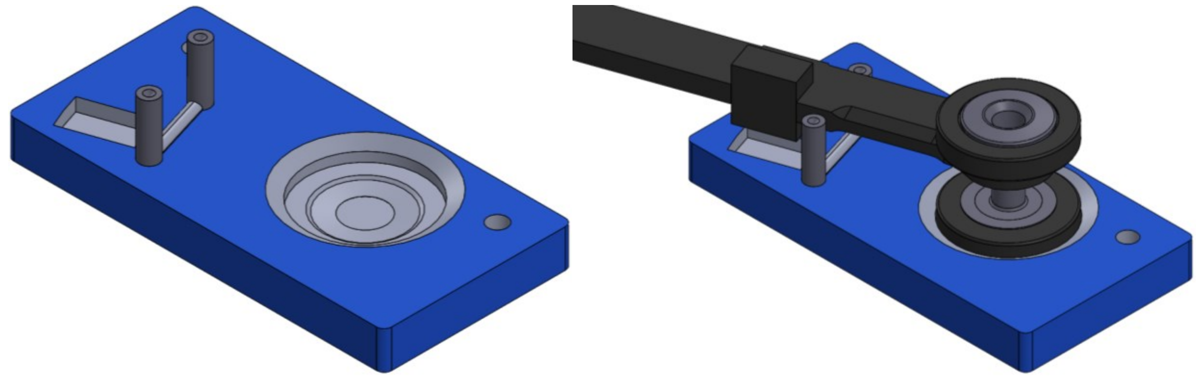

Figure R.5: Fixture for pressing the shaft with a roll into the lever, lever range 14”-18” with (r) and without the components (l).

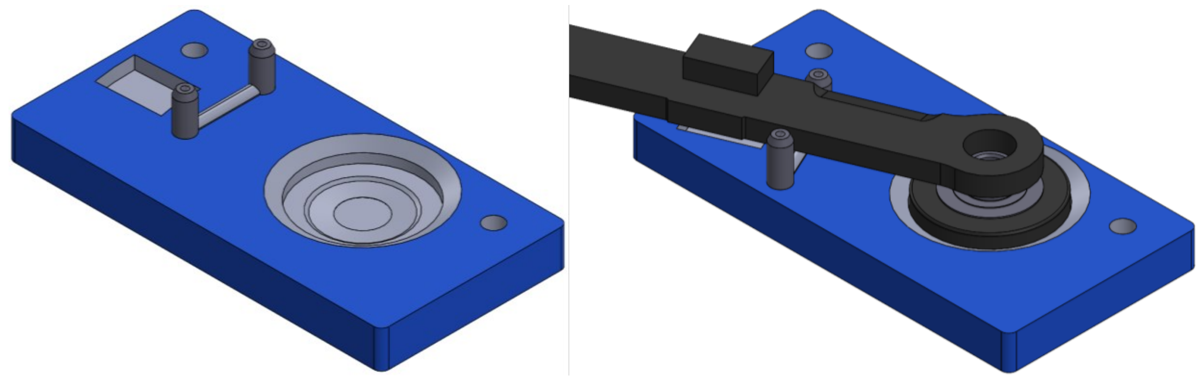

Figure R.6: Fixture for flaring the shaft of the rolls, lever range 14”-18” with (r) and without the components (l).

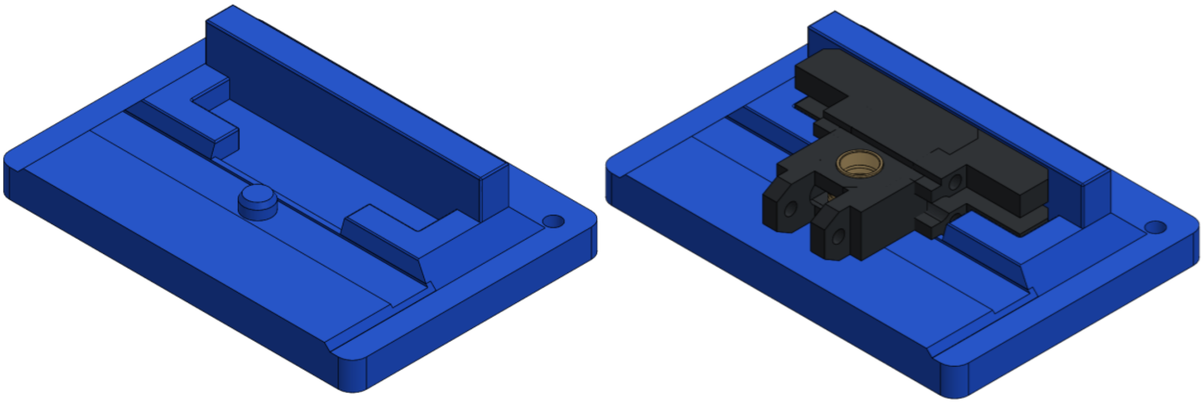

Figure R.7: Fixture for pressing the bush bearings into the pivot block, lever range 14”-18” with (r) and without the components (l).

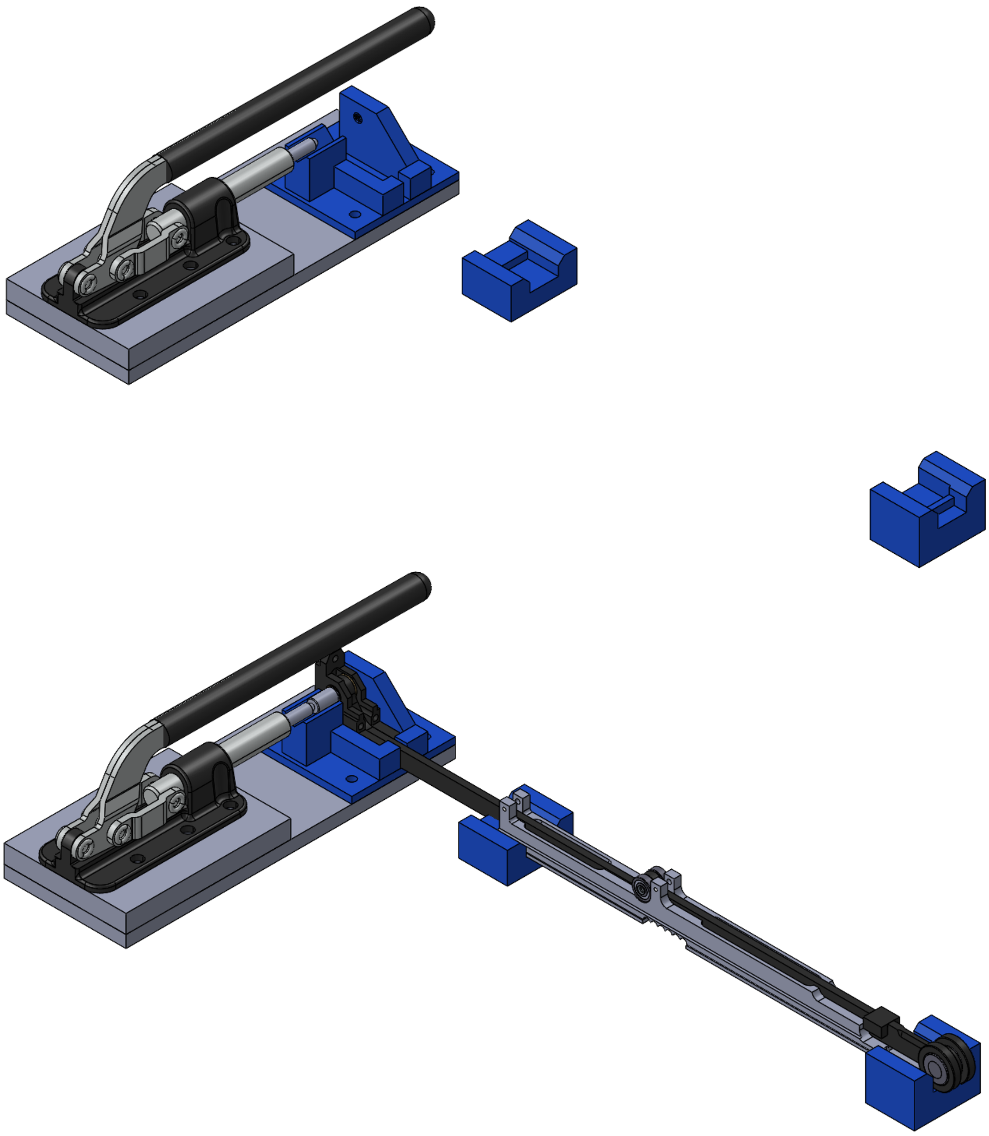

Figure R.8: Fixture for pressing the dowel into the lever base and pivot block, lever range 14”-18” with (b) and without the components (t).

R.2 Pressing tools lever assembly

Figure R.9 to Figure R.14 overview the pressing tools for the new process design of the lever.

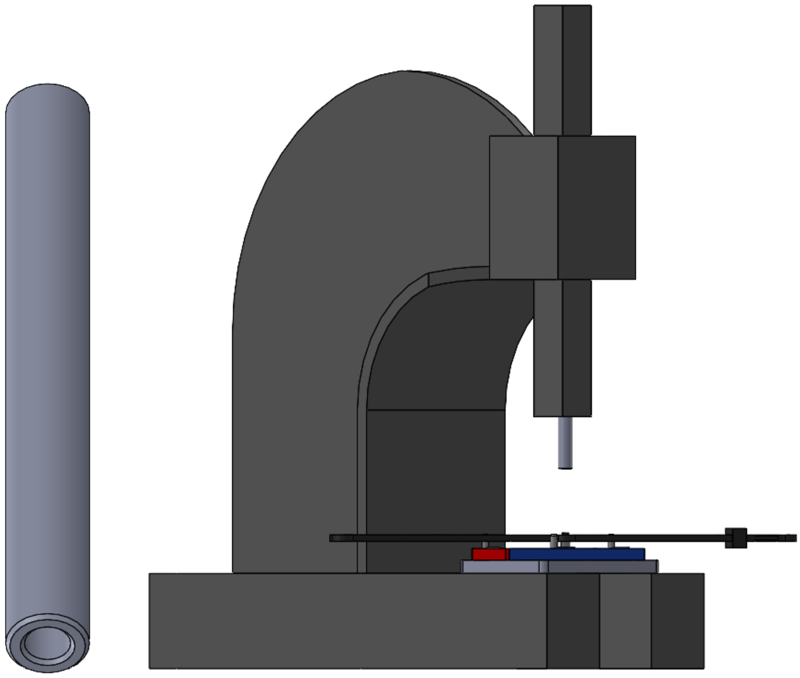

Figure R.9: Pressing tool for pressing the shaft for the ball bearings into the lever (l), and in the press with the fixture (r).

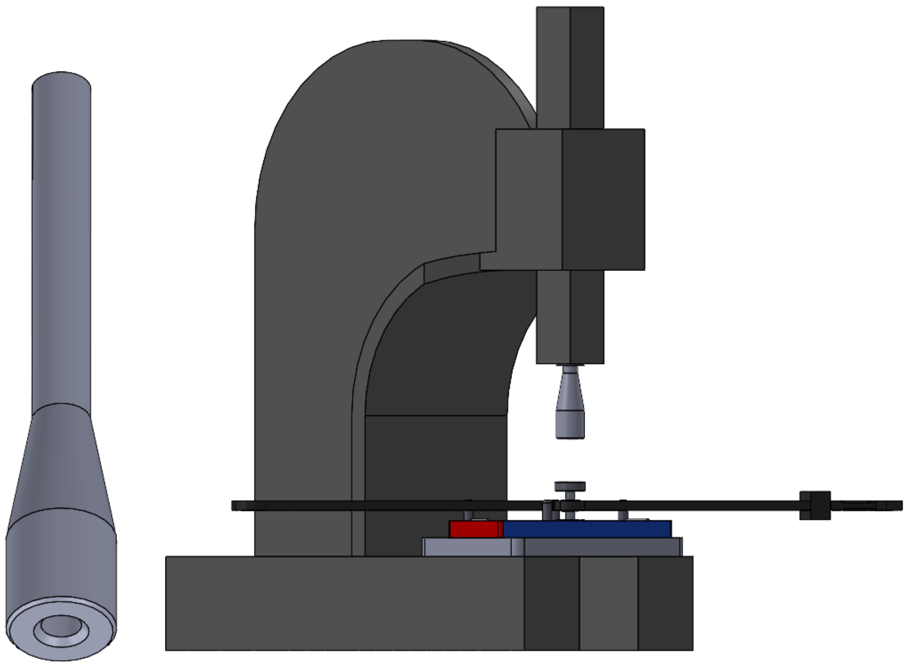

Figure R.10: Pressing tool for pressing the ball bearings onto the shaft (l), and in the press with the fixture (r).

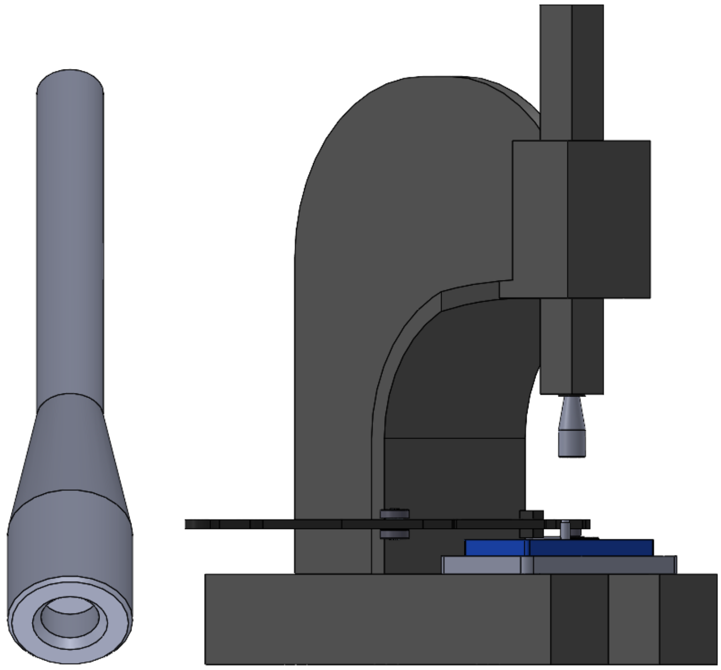

Figure R.11: Pressing tool for pressing the bush with a roll into the lever (l), and in the press with the fixture (r).

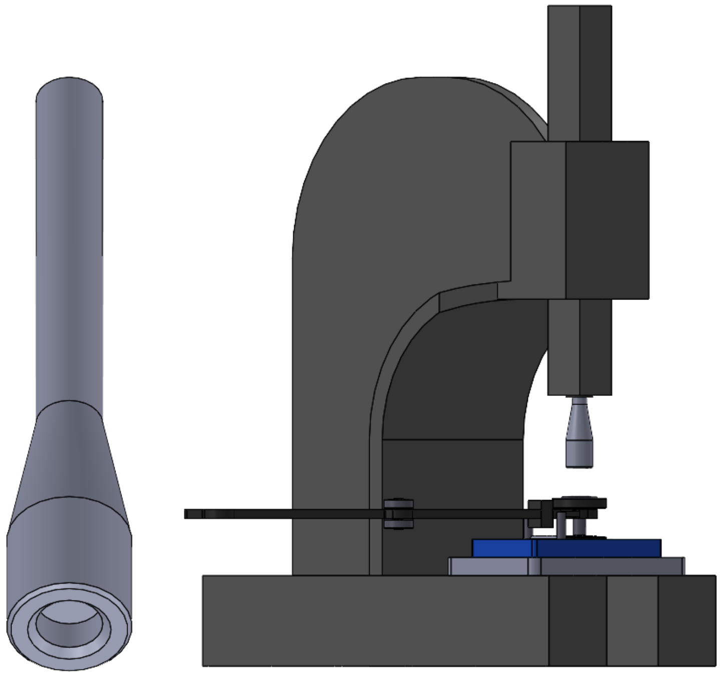

Figure R.12: Pressing tool for pressing the shaft with a roll into the lever (l), and in the press with the fixture (r).

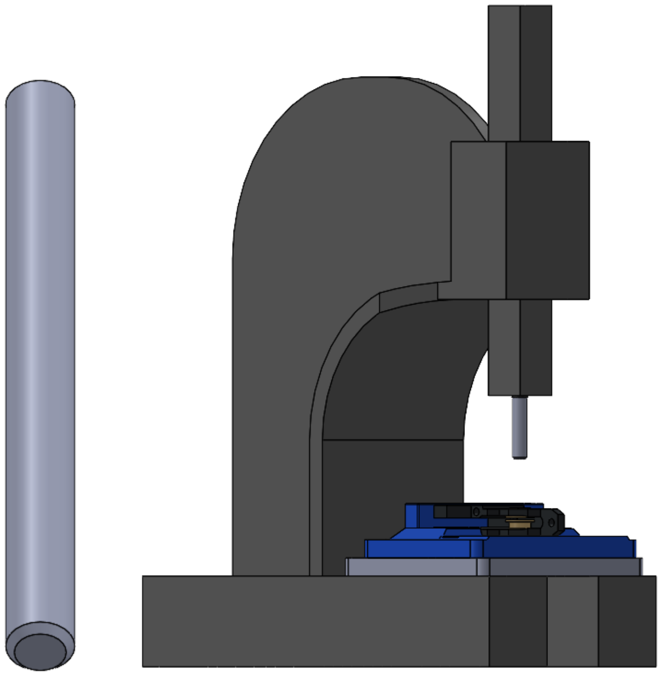

Figure R.13: Pressing tool for pressing the bush bearings into the pivot block (l), and in the press with the fixture (r).

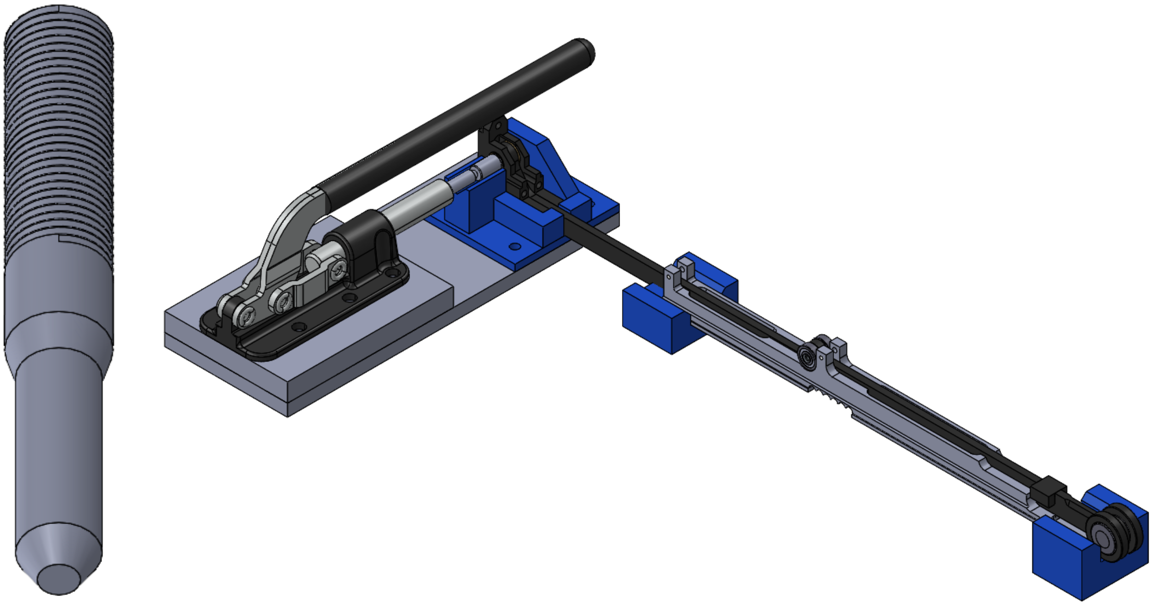

Figure R.14: Pressing tool for pressing the dowel into the lever base and pivot block (l), and in the press with the fixture (r).

Appendix S Risk inventory and evaluation

Appendix S elaborates on the risk inventory and evaluation of the new process design of the lever. It introduces in Section S.1 the method used: the Fine-Kinney method. Afterwards, Section S.2 presents the results and discusses the validity of the results.

S.1 Fine-Kinney method

In the first performance measurement, we excluded safety because the number of (near) incidents of the lever production process was only one between 2016 and 2020. However, with a new process design of lever, potential safety risks may have emerged. To inventory and evaluate potential safety risks, we carry out a RI&E. As mentioned, it lists health and safety risks per work activity and assesses the likelihood of occurrence, duration, and effect of a hazard on the employees. We use the Fine-Kinney method to expose risk factors, a widely used method for risk assessment (Gul, Mete, Serin, & Celik, 2021). It uses a risk score, the product of risk exposure, likelihood, and impact severity. These three factors have scales, given in Table S.1 to Table S.3. Afterwards, the evaluation of the risk scores defines the subsequent actions. For this purpose, the method suggests five potential actions based on the risk score given in Table S.4 (Gul et al., 2021). The RI&E compares the current state with the future state lever assembly process. In addition, it specifies subsequent actions and due dates based on the risk scores.

Table S.1: Probability scale of Fine-Kinney method.

Value	Probability of undesired event
10	Expectations that happens
6	Very likely
3	Unusual, but possible
2	Only remotely possible
1	Very unlikely
0.5	Almost impossible

Table S.2: Exposure scale of Fine-Kinney method.

Value	Exposure of undesired event
10	Continuous
6	Regular (daily)
3	Occasionally (weekly)
2	Unusual (monthly)
1	Rare (a few per year)
0.5	Very rare (yearly)

Table S.3: Consequence scale of Fine-Kinney method.

Value	Consequence of undesired event
100	Catastrophic (many fatalities)
40	Disaster (few fatalities)
15	Very serious (one fatality)
7	Serious (serious injury)
3	Important (disability)
1	Noticeable (first aid accident)

Table S.4: Risk scale of Fine-Kinney method

Risk score	Risk situation	Priority
R > 400	Very high risk – consider discontinuing operation	1
200 < R ≤ 400	High risk – immediate correction required	2
70 < R ≤ 200	Substantial risk – correction needed	3
20 < R ≤ 70	Possible risk – attention indicated	4
R ≤ 20	Risk – perhaps acceptable	5

S.2 Results and validity risk inventory and evaluation

The second section presents the results of the RI&E in subsection S.2.1. Furthermore, it discusses the validity of the results in subsection S.2.2.

S.2.1 Identification and evaluation of risks

The RI&E compared the current state with the future state lever assembly process. It specified three main activities material preparation, assembly, and storing of finished products. Subsequently, it elaborates per activity potential risks, for instance, physical workload, falling materials, and risk of cutting when storing finished products. The risk scores reveal that the current lever assembly process has quite a few high-risk activities, listed in column H of Figure S.1. The activity with the highest risk is glueing the bush bearings. As mentioned, the fumes of the adhesive are carcinogenic in case of prolonged exposure . Then, the RI&E mentions control measures for all the potential risks and provides additional information on these control measures, given in columns L and N of Figure S.1. These measures are aspects we already included in the new design of the lever assembly process. Afterwards, the RI&E lists the risk scores in the future state in column S of Figure S.1. The control measures reduce the probability of a risk, but the effect and consequence remain the same. After the second evaluation, we formulated three subsequent actions. The first is the active monitoring of the ergonomic conditions, discussed in more detail in subsection 7.4.4. The other two relate to design changes. One is the design change of the slide block, presented in subsection 6.2.4. The other is the engineering fit between the bush bearing and the pivot block, mentioned in more detail in subsection 7.2.1. If those responsible for these three actions carry them out, all the formulated potential risks can be considered acceptable.

S.2.2 Validity risk inventory and evaluation

We presented the RI&E of the current and future state lever assembly process to the QESH department since they have the knowledge and experience in creating RI&Es. The feedback of QESH was that the potential risks cover all areas and are realistic. In addition, the scales used for probability, effect, and consequence per risk are appropriate, and thus the risk scores are suitable. The three formulated subsequent actions are logical given the risk scores. Therefore, QESH approved the RI&E and published it to the internal network of VMI. Thus, the RI&E of the future state lever assembly is reliable and valid.

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A	B	C	D	E	F	G	H	I	J	K	L	M
RI&E subject	**Main activity**	**Risk applicable?**	**Description risk**	**Effect**	**Probability**	**Consequence**	**Risk score**	**Risk situation**	**Measure**	**Priority**	**Control measures**	**Responsibility**
	Material preparation	Yes	Physical load									
	Material preparation	Yes	Falling materials									
	Material preparation	Yes	Risk of cutting									
	Assembly	Yes	Physical load									
	Assembly	Yes	Repetitive motions						*Confidential*			
Lever assembly	Assembly	Yes	Risk of cutting									
	Assembly	Yes	Hitting fingers with a hammer									
	Assembly	Yes	Gluing of pivot block									
	Assembly	Yes	Pinch point hazard									
	Storing finished products	Yes	Physical load									
	Storing finished products	Yes	Falling materials									
	Storing finished products	Yes	Risk of cutting									

N	O	P	Q	R	S	T	U	V	W	X	Y
Additional information	**Control measure sufficient?**	**Effect**	**Probability**	**Consequence**	**Risk score**	**Risk situation**	**Measure**	**Priority**	**Subsequent actions?**	**Addtional information**	**Due date**
									No		
									No		
									No		
									Yes	Active monitoring ergonomics - potential long term risk	Q1 2022
									Yes	Active monitoring ergonomics - potential long term risk	Q1 2022
	Confidential								No		
									Yes	Approval by Engineering	Q1 2022
									Yes	Approval Engineering for design change	asap
									No		
									No		
									No		
									No		

Figure S.1: RI&E over the lever assembly in the current and the future state.

Appendix T Capability study bush bearings and pivot block

A group of students performed a capability analysis of the engineering fit between the bush bearings and the pivot block. For this purpose, they measured the bore diameters in 30 pivot blocks and 30 outside diameters of bush bearings. Using the specification limits (i.e., component tolerances), the students determined that the mean of both dimensions is close to

. Figure T.1 and Figure T.2 give the process capability plots of the pivot block and bush bearing, respectively. They show the

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Figure T.1: Process capability plot of the outside diameter of the bush bearings.

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Figure T.2: Process capability plot of the bore diameter in the pivot blocks.

As these two components mate, the students also evaluated the fit between them. To do so, the students merged the two process capability plots, depicted in Figure T.3. It reveals that the mean

. Ideally, the mean of the outside bush bearing diameter is equal to or slightly larger than the mean of the bores in the pivot blocks. Then, the probability of a bush bearing falling out of the pivot block is small.

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Figure T.3: Process capability plot of the outside diameter of the bush bearings (blue) and bore diameter in the pivot blocks (red).

Appendix U Process measurement script

The process measurement script lists subjects (e.g., fixture and pressing tool) and potential incidents (e.g., damaged and damaged beyond repair) per subject that can occur. Furthermore, it mentions, based on these incidents, the subsequent actions (e.g., pause and stop process measurement) we would need to carry out when the incident occurs during the process measurement.

Accident

Situation	Action
Accident, no injury	1. Stop process measurement - record time 2. Report accident 3. Determine cause 4. Improve working conditions
Accident with injury	1. Call BHV 2. Stop process measurement - record time 3. Report accident 4. Determine cause 5. Improve working conditions

Fixture

Situation	Action
Damaged	1. Pause process measurement - record time 2. Damage assessment 3. Follow-up steps: a. Repair, restart b. Replacement, end of process measurement
Broken	1. Stop process measurement - record time 2. Print a new fixture

Materials

Situation	Action
Fallen	1. No actions
Damaged	1. Table of Sin 2. No actions (component quality)
Wrong materials	1. Pause process measurement - record time 2. Fetch materials 3. Resume process measurement - record time
Shortage	1. Pause process measurement - record time 2. Fetch materials 3. Resume process measurement - record time
Surplus	1. No actions

Manual press

Situation	Action
Loosened from table	1. Pause process measurement - record time 2. Secure press 3. Resume process measurement - record time
Loosened from table and fallen	1. Stop process measurement - record time 2. Report accident 3. Damage assessment 4. Repair press 5. Secure press differently
Jammed	1. Pause process measurement - record time 2. Damage assessment 3. Follow-up steps: a. Quick repair, restart b. Extend repair, end of process measurement
Loosened stamp	1. Pause process measurement - record time 2. Damage assessment 3. Follow-up steps: a. Quick repair, restart b. Extend repair, end of process measurement
Handle damaged	1. Pause process measurement - record time 2. Damage assessment 3. Follow-up steps: a. Quick repair, restart b. Extend repair, end of process measurement
Pressing requires heavy forces	1. Pause process measurement - record time 2. Damage assessment 3. Follow-up steps: a. Quick repair, restart b. Extend repair, end of process measurement

Pneumatic screwdriver

Situation	Action
Fallen	1. No actions
Damaged	1. Pause process measurement - record time 2. Replace screwdriver 3. Resume process measurement - record time
Broken	1. Stop process measurement - record time 2. Repair/order new screwdriver 3. Resume process measurement - record time
Bit damaged/broken	1. Pause process measurement - record time 2. Replace bit 3. Resume process measurement - record time
No air pressure	1. Stop process measurement - record time

Pressing tool

Situation	Action
Loosened	1. Pause process measurement - record time 2. Secure pressing tool 3. Resume process measurement - record time
Damaged	1. Pause process measurement - record time 2. Damage assessment 3. Follow-up steps: a. Quick repair, restart b. Extend repair, end of process measurement
Broken	1. Stop process measurement - record time 2. Order new pressing tool

Process quality

Situation	Action
Rejected lever	1. Table of Sin 2. No actions (process quality)

Two-bin flow racks

Situation	Action
Fallen from table	1. Stop process measurement - record time 2. Report accident 3. Damage assessment 4. Follow-up steps: a. Repair, restart b. Replace, end of process measurement 5. Secure two-bin flow racks
Fallen over	1. Pause process measurement - record time 2. Damage assessment 3. Follow-up steps: a. Quick repair, restart b. Replacement needed, remove and restart
Material bin tipped over	1. No actions

Appendix V Monte Carlo simulation & hypothesis test

Appendix V elaborates on the Monte Carlo simulation used to substitute the cycle times of the baseline performance in Section V.1. Furthermore, it explains the approach followed for selecting the one-sample Wilcoxon test and the required sample size to perform the test in Section V.2.

V.1 Monte Carlo Simulation of cycle times

A Monte Carlo simulation is a technique that uses repeated random sampling to generate results. It samples values at random from the input probability distributions. Each set of samples is an iteration, and one Monte Carlo simulation performs thousands of iterations to generate results (Palisade, n.d.). The Monte Carlo simulation to obtain new cycle times uses input data from the baseline performance. The photos of the work sampling study allow determining the start and finish time of 30 batches per assembly step. Since we know the size of every batch, we can determine the cycle time per lever per assembly step. The Monte Carlo simulation samples values using a pseudo-random number generator, and the variables of every assembly step follow a uniform distribution. So, all values have an equal chance of occurring. A set of five cycle times, one for every assembly step, is the cycle time of one lever. The number of iterations is 10 thousand, more than the eight thousand suggested by Mundform et al. (2011) to obtain stable results. The probability that two iterations have a similar set of cycle times is one in 24.3 million.

The Monte Carlo simulation results in a mean of seconds (minutes), a standard deviation of seconds (minutes), and a median of seconds (minutes) visualised in Figure V.1. The mean deviates only slightly from the seconds (minutes) of simulation input data and seconds (minutes) of the ERP data. Hence, the simulation results seem to be satisfactory substitutes for the baseline performance. The next step is to select a suitable hypothesis test that we can use to determine whether the cycle time of the lever has significantly reduced.

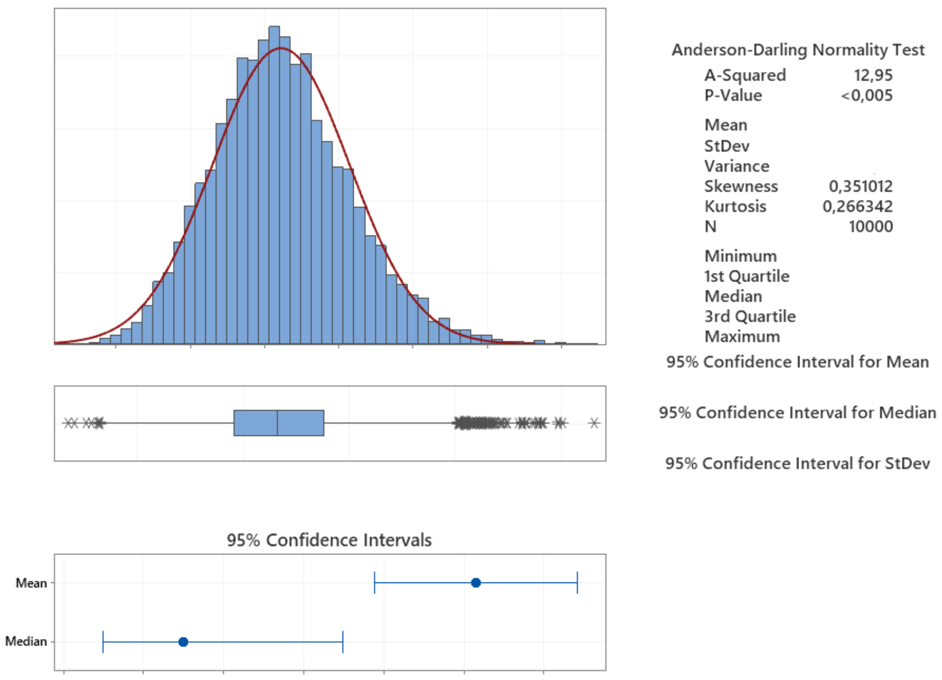

Figure V.1: Graphical summary of the Monte Carlo simulation results.

V.2 Hypothesis testing cycle time

The Monte Carlo simulation has generated substitute data for cycle times of the baseline performance. The next step is to select a suitable hypothesis test and to determine a sample size that is sufficiently large to perform the selected test. It starts with fitting probability distributions to the Monte Carlo simulation results in subsection V.2.1. Then, subsections V.2.2 discusses potential non-parametric tests and selects one. Subsection V.2.3 determines the minimum sample size for the one-sample Wilcoxon test. Afterwards, subsection V.2.4 examines the standard error and confidence interval of the standard error for varying sample sizes. Subsection V.2.5 studies the power of the one-sample Wilcoxon test. Subsequently, subsection V.2.6 summarises the selection approach of the hypothesis test and the aspects included in the sample size selection.

V.2.1 Identification of probability distributions

Various hypothesis tests exist to examine the differences between population parameters such as means, proportions, and variances. However, many of these tests, the parametric tests, assume that the population follows a probability distribution, generally the normal distribution. Thus, we first need to determine which probability distribution the Monte Carlo data follows. For this purpose, we use the function distribution identification in Minitab. It performs goodness-of-fit tests to determine which distribution provides the best fit and whether a data transformation is effective to fit the data to a normal distribution.

The distribution identification concludes with a 95% confidence level that none of the 14 probability distributions fit the Monte Carlo data, given in Figure V.2. The p-values of all distributions are lower than 0.05 and thus not significant. Hence, we cannot use parametric tests because we cannot assume that the Monte Carlo data follows a probability distribution. However, we can use the Johnson transformation since it is significant. A data transformation to normally distributed data could be beneficial because we can use more hypothesis tests. By contrast, transformed data is hard to interpret or compare. It generally requires back-transformation, which may be a complex process. Moreover, normally distributed data is not a condition to perform hypothesis tests. Non-parametric tests, for example, suit data of which no distribution can be assumed and also guarantee a scientific result (Lee, 2020). Therefore, we first review the applicability of non-parametric tests before considering a data transformation.

Distribution	AD	P	LRT P
Normal	12,955	<0,005	
Box-Cox Transformation	0,838	0,031	
Lognormal	2,417	<0,005	
3-Parameter Lognormal	0,756	*	0,000
Exponential	3366,406	<0,003	
2-Parameter Exponential	2135,719	<0,010	0,000
Weibull	100,154	<0,010	
3-Parameter Weibull	20,399	<0,005	0,000
Smallest Extreme Value	231,345	<0,010	
Largest Extreme Value	55,816	<0,010	
Gamma	0,947	0,018	
3-Parameter Gamma	0,903	*	0,119
Logistic	11,196	<0,005	
Loglogistic	5,580	<0,005	
3-Parameter Loglogistic	4,989	*	0,025
Johnson Transformation	0,467	0,251	

Figure V.2: Goodness of fit test of the Monte Carlo Simulation results against 14 probability distributions and two data transformations.

V.2.2 Non-parametric tests

The non-parametric tests do not assume that the data follows a probability distribution. They often examine the difference between population medians. Various non-parametric tests exist to compare the medians of one, two, or more samples. The Monte Carlo simulation yielded the hypothetical median, a target value we can compare to a sample median. The non-parametric tests one-sample sign test and the one-sample Wilcoxon test are suitable for this purpose. The first test has no additional conditions, whereas the latter assumes the data is symmetrically distributed. However, the results of the Monte Carlo simulation show slightly skewed data, listed in Figure V.1. It has a skewness of 0.35, which is not very odd considering the seven seconds difference between the mean and median. Data without any skewness has a mean equal to the median. However, a skewness between -0.5 and 0.5 indicates the distribution is fairly symmetrical (McNeese, 2016; Oracle, 2012). When both are available and applicable, Usman (2015) suggested using the one-sample Wilcoxon test rather than the one-sample sign test. It is more power-efficient since it requires a smaller sample size to obtain the same result. Furthermore, it is slightly more powerful than the one-sample sign test. Thus, we use the one-sample Wilcoxon test as the hypothesis test to examine whether the cycle time of the lever has significantly reduced. We continue by determining the minimum sample size to perform the one-sample Wilcoxon test.

V.2.3 Minimum sample size one-sample Wilcoxon test

Al-Sunduqchi (1990) described an approach to determine the appropriate sample size for a one-sample Wilcoxon test. It first determines the minimum sample size using a one-sample t-test and subsequently uses adjustment factors based on the assumed data distribution. Before we can use the one-sample t-test, we first have to estimate the expected cycle time of the levers in the future state. For this purpose, we use the results of the work sampling study given in Table V.1. It shows how much time the employees spent on activities per assembly step. For example, when the employees join the lever base to the pivot block, they use almost % of the time on repairs. We estimate the percentage in the future process per activity category. For instance, we expect the time spent on material handling to reduce from % to % per assembly step. Some of the reasons are the U-shaped layout, one-piece flow, and components placed in the process. This process repeats for every activity category of the first three assembly steps of the new process design. The last two, pressing the bush bearings and joining the lever base to the pivot block, are new assembly methods. For these two, we estimate the processing time based on five assembly trials adjusted by a factor to incorporate non-assembly-related activities. Lastly, we include additional time to the five processing times to compensate for the component and process quality, learning curves, and the plastic fixtures. Table V.2 lists the expected processing times per assembly step in the future state assembly process. It shows that the expected cycle time of a lever reduces by % to minutes. A first indication that the research objective to increase the process capacity by 15% is achievable.

Table V.1: Time distribution per activity per assembly step.

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Table V.2: Expected processing times and reduction compared to current processing time per assembly step.

Assembly step	Expected processing time [min]	Reduction
Pressing bearings		%
Pressing rolls		%
Mounting slide block		%
Pressing bush bearings		%
Joining lever base to the pivot block		%
Total		%

The expectation is a reduction of the cycle time by %. Thus, the sample mean ($\bar{X}$) becomes seconds in the one-sample t-test. The hypothetical mean (μ_0) is seconds, and the standard deviation (s) is seconds. These values originate from the Monte Carlo simulation. If we return these values to equation V.1, the one-sample t-test, we can determine the t-value by filling in a sample size (n). The outcome is the observed t-value. If it is greater than the critical t-value, the sample size is sufficient. We determine the critical t-value for a one-sided test, with a confidence interval of 95% and the degrees of freedom equal to the sample size minus one. If the observed t-value is smaller than the critical t-value, we increase the sample size by one. However, to prevent overestimating the cycle time reduction, we determine the minimum sample size for a range of sample means. The sample means range from a reduction of % to % in cycle time. Figure V.3 shows the minimum sample size per % reduction in the cycle time. For instance, the minimum sample size for a % reduction is and for an % reduction in cycle time. If we check these findings by using the one-sample t-test in Minitab, they give the same results. A cycle time reduction of % requires a minimum sample size of .

$$t = \frac{\bar{X} \cdot \mu_0}{s/\sqrt{n}} \tag{V.1}$$

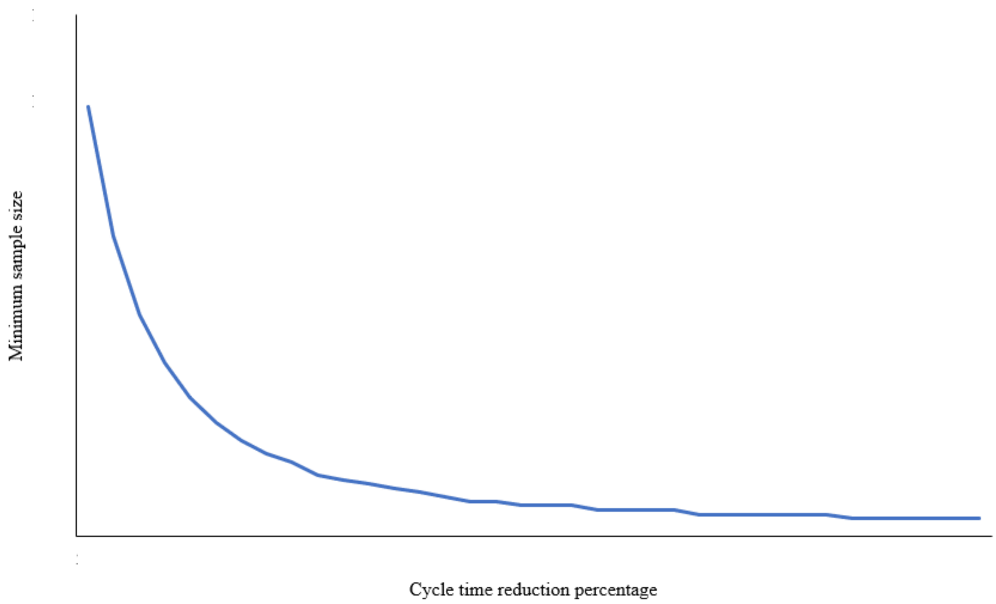

Figure V.3: Minimum sample size per percent cycle time reduction based on the one-sample t-test.

We determined the minimum sample sizes for a range of cycle time reductions. The subsequent step is to use the adjusted factors suggested by Al-Sunduqchi (1990) to determine the minimum sample size for the one-sample Wilcoxon test. The minimum sample size of the one-sample Wilcoxon test is equal to the minimum sample size of the one-sample t-test divided by the adjustment factor. Al-Sunduqchi (1990) based the adjustment factors on the assumed data distribution, given in Table V.3. However, we cannot make assumptions about the data distribution, as Figure V.2 shows that none of the data distributions fitted. Therefore, we choose to select the adjustment factor that impacts the sample size the greatest: the double exponential. Figure V.4 shows the minimum sample sizes per % reduction in the cycle time for the assumed distributions. It shows that the impact of the adjustment factor is high with a lower reduction in cycle time, and from % onward, the impact on the minimum sample size is small. So, to determine a % reduction in the cycle time, we need a minimum sample size of . We check this finding by using the one-sample Wilcoxon test in Minitab. Therefore, we use iterations of the Monte Carlo simulation and deduct seconds from their cycle times. It proves the minimum sample size is with a confidence level of 95%.

Table V.3: Adjustment factor for the sample size per assumed probability distribution (PASS, 2021).

Assumed probability distribution	Adjustment factor	Assumed probability distribution	Adjustment factor
Double exponential	2/3	Normal	$\pi/3$
Logistic	$9/\pi^2$	Uniform	1

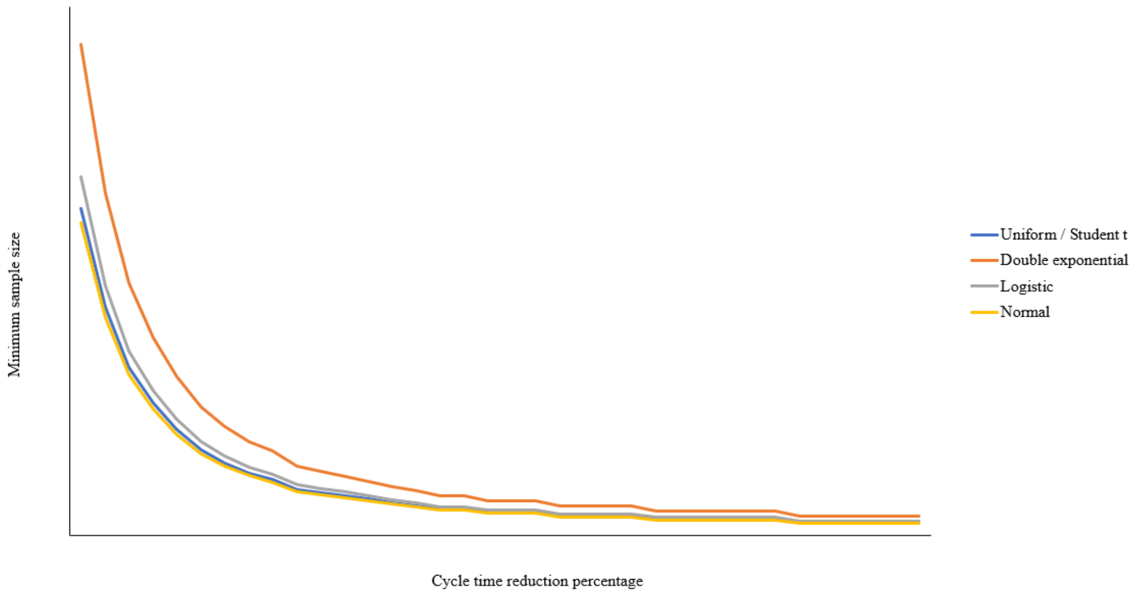

Figure V.4: Minimum sample size per percent cycle time reduction adjusted for the assumed probability distribution.

V.2.4 Standard error and confidence interval standard error

Given the low minimum sample size, we want to ensure the standard error and its confidence interval are not too great. Therefore, we examine them with five Monte Carlo Simulations. We start with the values of ten iterations and evaluate the standard error and confidence interval of the standard error. Subsequently, we add ten more values and repeat the evaluations till we have 200 cycle times per scenario. We aim to determine a sample size where the standard error is close to its actual value and does not fluctuate too much. Also, we aim to find the sample size where the confidence interval decreases only minimally. Table V.4 lists the standard errors and their confidence intervals per sample size for the five scenarios. It shows that the standard errors do not fluctuate too much with a sample size of 80-90. Furthermore, the standard errors are around their actual value, given in the bottom row. Figure V.5 shows the decrease in confidence interval per sample size for the five scenarios. It reveals that the confidence intervals decrease slowly from 60 samples. At a sample size of 100, the decline in the confidence interval is minimal. Logical since the standard error decreases by the square root of the sample size. Hence, increasing the sample size further only causes minor declines in the confidence interval of the standard error. Therefore, we select a sample size of 100 levers.

Table V.4: Standard error and confidence interval of the standard error per sample size over the scenarios.

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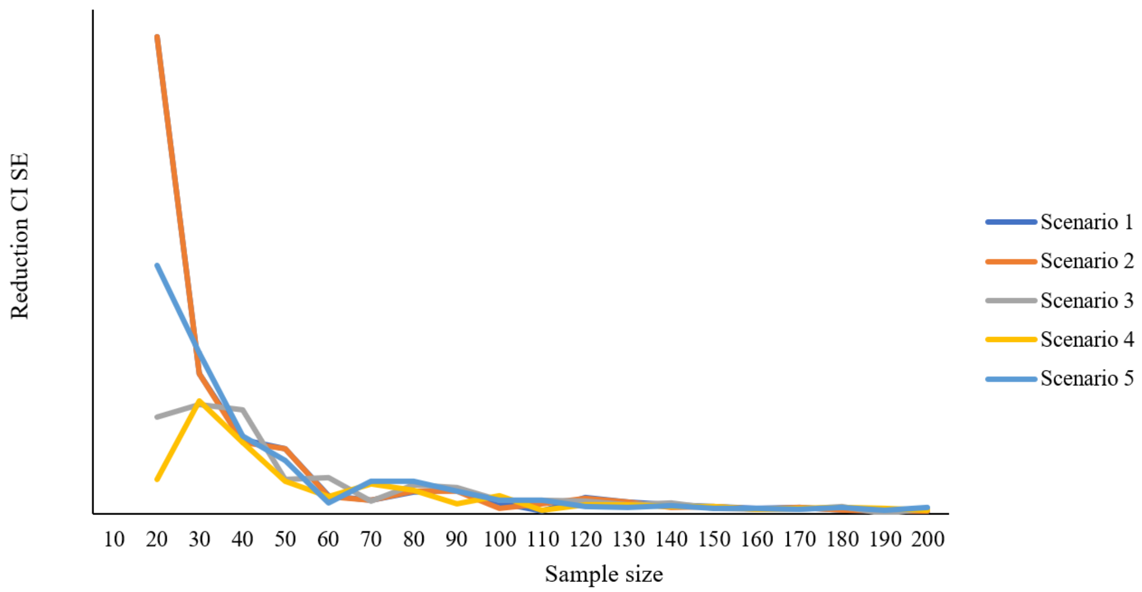

Figure V.5: Reduction of the confidence interval of the standard error per sample size over the scenarios.

V.2.5 Power one-sample Wilcoxon test

With the sample size of 100 products, we need to ensure the power of the one-sample Wilcoxon test is also sufficient. The higher the power level, the lower the probability of failing to reject the null hypothesis. Al-Sunduqchi (1990) described the power calculation for the one-sample Wilcoxon test as equal to the power calculation of the one-sample t-test, except it uses the adjusted sample size. The procedure for a one-sided test where $u_1 < u_0$ is as follows:

$$1 - T_{df}(t_\alpha) = \alpha \tag{V.2}$$

$$X_1 = \mu_0 + t_\alpha * \sigma/\sqrt{n'} \tag{V.3}$$

$$\lambda = \frac{\mu_1 - \mu_0}{\sigma/\sqrt{n'}} \tag{V.4}$$

$$\lambda = \frac{X_1 - \mu_1}{\sigma/\sqrt{n'}} + \lambda \tag{V.5}$$

$$1 - T'_{df,\lambda}(t_1) \tag{V.6}$$

Equation V.2 finds a value for t_α where $T_{df}(t_\alpha)$ is the area under the Student's t-distribution to the right of x, and the degrees of freedom (df) is equal to the adjusted sample size (n') minus one. The second equation, V.3, determines the sample mean using the standard one-sample t-test using the adjusted sample size. Afterwards, equation V.4 computes the non-centrality parameter λ. Equation V.5 determines the observed t-value, where it includes the λ. Then, equation V.6 calculates the power value where $T'_{df,\lambda}$ is the area to the right of x under the non-central t-distribution with non-centrality parameter λ and the degrees of freedom df.

The non-central t-distribution is a recursive function. It requires an algorithm for recursive computing. Fortunately, several statistical software programs have implemented such a function that performs the recursive computing of the non-central t-distribution. We decide to use one (PASS) since the research focus is not on creating an algorithm to calculate the power. The input values are the seconds mean and seconds standard deviation of the Monte Carlo simulation. The confidence level is 95%, the sample size is 100, and the test is one-sided ($u_1 < u_0$). Moreover, we again use a range of sample means between a % and % reduction in cycle time to include some rigidity. The same approach we used to determine the minimum sample size. Table V.5 lists the power values for the different sample means at a sample size of 100. It gives a power value of 95% when the sample mean only reduces by %. A reduction in the sample mean from % onward have a power value of 100% or one. So, if the cycle time of the levers decreases by %, we have a zero probability of failing to reject the null hypothesis.

Table V.5: Power value per percentage reduction of the cycle time with a sample of 100.

Cycle time reduction percentage	*Confidential*							
Power value (n=100)	95.4%	100%	100%	100%	100%	100%	100%	100%

V.2.6 Conclusion

So, we can use the one-sample Wilcoxon test to determine whether the cycle times significantly differ between the results of the Monte Carlo simulation and Proof of Concept. For this purpose, we use a sample size of 100 levers. The sample size is sufficiently large to conclude with a 95% confidence level and 95% power value, a cycle time reduction of only %. Furthermore, the standard error approaches its true value with a sample size of 100, and the confidence interval of the standard error only reduces from 100 samples onward only slightly. Thus, we proved that a non-parametric test is applicable to determine a significant difference in the cycle times, and we do not need a data transformation.

Appendix W Additional information future state lever assembly

The TOS and hypothesis testing are part of determining the future performance of the lever assembly process. Section W.1 provides additional background information about the TOS and its use for determining the FTR percentages per assembly step. Section W.2 provides the summary reports of the hypothesis testing. The hypothesis testing determined whether the current state and future state significantly differ in quality and cycle time.

W.1 Quality aspects future state lever assembly

The first section provides an overview of the quality aspects of the future state performance of the lever assembly process. Figure W.1 illustrates the TOS with the defective components and rejected levers after the proof of concept. Figure W.2 to Figure W.6 use the TOS to determine the FTR percentages per assembly step. These figures compare the current state with the future state performance.

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Figure W.1: TOS with the items having component (b) and process quality issues (t) after the proof of concept.

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Figure W.2: FTR-% of pressing the bearings in the current and future state lever assembly process.

Confidential

Figure W.3: FTR-% of pressing the rolls in the current and future state lever assembly process.

Confidential

Figure W.4: FTR-% of mounting the slide block in the current and future state lever assembly process.

Confidential

Figure W.5: FTR-% of pressing the bush bearings in the current state and future state lever assembly process.

Confidential

Figure W.6: FTR-% of joining the lever base to the pivot block in the current and future state lever assembly process.

W.2 Summary reports hypothesis testing

The second section presents the summary of the hypothesis testing. It first gives the outcomes of the two-sample defective % test in Figure W.7. Then, the summary report of the one-sample Wilcoxon test in Figure W.8. Finally, it presents the power value for the median in Figure W.9.

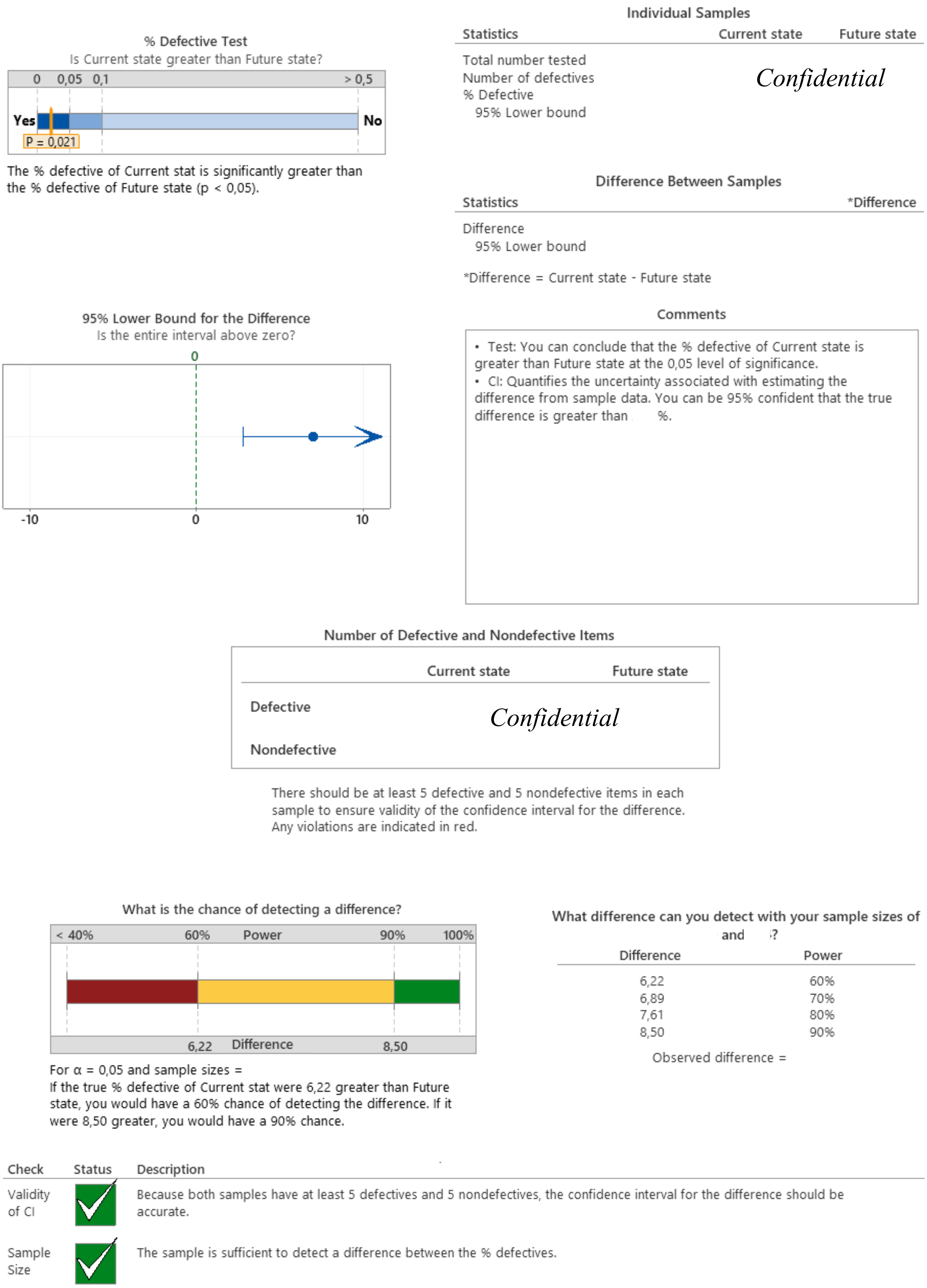

Figure W.7: Summary report of the two-sample defective % test.

Wilcoxon Signed Rank Test: CT

Method

η: median of CT

Descriptive Statistics

Sample	N	Median
CT	100	

Test

Null hypothesis H_0: η =
Alternative hypothesis H_1: η <

Sample	N for Test	Wilcoxon Statistic	P-Value
CT	100	0,00	0,000

Figure W.8: Summary report of the one-sample Wilcoxon test.

Power and Sample Size

1-Sample t Test
Testing mean = null (versus < null)
Calculating power for mean = null + difference
α = 0,01 Assumed standard deviation =

Results

Difference	Sample Size	Power
	100	1

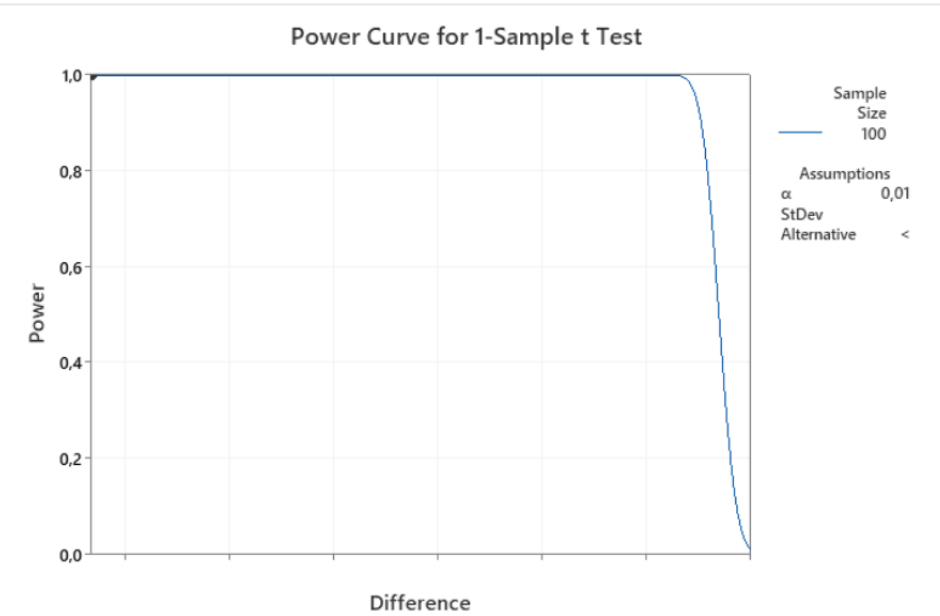

Figure W.9: Summary report of the power value using one-sample t-test.

Appendix X Workload balancing future state lever assembly

The production process design of the lever is flexible to changeover relatively quickly between the different lever varieties. However, it has to be flexible to cope with variability in the workload. Increasing the capacity of a process by adding additional employees to the assembly process is a solution to cope with workload variability. Nevertheless, the workload between employees should not differ too much. Therefore, Section X.1 mentions three potential operating modes to balance the workload and afterwards selects one. Next, Section X.2 proposed the workload balancing for the lever assembly in the future state.

X.1 Operating mode

Operating modes can balance the workload in case multiple employees are assembling levers. Calzavara, Faccio, Persona, and Zennaro (2021) listed three operating modes to balance the workload over the employees:

- Rabbit chase — Each employee travels along the entire line with the product and performs the required tasks per workstation.
- Bucket brigades — Each employee performs tasks on a product from one workstation to another until the next employee resumes his or her work. The employee returns to start a new product or continue the work of his or her predecessor.
- Baton touch — Each employee is assigned to multiple workstations, not necessarily consecutive.

Miralles, Garcia-Sabater, Andres, and Cardos (2007) specified several aspects to consider when balancing the workload in a sheltered workshop. The mean processing time for a task usually differs greatly per employee. Furthermore, the variability in processing times for a sheltered workshop employee is higher. These two aspects impact the operating mode rabbit chase. In a rabbit chase, the slower employee limits the system speed and may cause the faster employee to wait (Alves, 2018). The future state lever assembly has a cycle time of minutes, and the process step with the highest workload (i.e., mounting the slide block) has a mean processing time of seconds. Hence, when two or more employees assemble levers, it is most likely employees queue in front of this process step. The result is an undesired productivity loss. The self-balancing aspect of the bucket brigades overcomes fluctuations in processing times since tasks are not assigned to employees. It requires that the employee are sequenced from slowest to fastest to allow self-balance (Alves, 2018). However, this impacts especially the slower employees by, for example, neglecting working conditions. They perform more repetitive, monotonous work. Moreover, there is a risk of upsetting the slowest employees by highlighting their slow pace by positioning them at the start of the process (Fagerudd & Jönsson, 2007). Lastly, a productivity loss may occur when employees proceed with the product from their predecessor. The bucket brigades generally have the policy that if the employees start one assembly task, they should complete it. Then, it may happen that the downstream employees cannot proceed with assembly from the upstream employees immediately after they are available and thus wait till the predecessor has finished (Koo, 2020). Splitting the task is a solution but requires clear communication between employees. Providing information visually is an effective way of communicating and coordinating in a sheltered workshop (Miralles et al., 2007). However, it is more likely that the communication and coordination time is longer than finishing the process task. The mean processing times at presses one, three, and six are, for example, under seconds. The baton touch operating mode can also overcome fluctuations in processing times and productivity loss by including small buffers before the decoupling points, similar to the drum-buffer-rope principle of TOC. Furthermore, since the employees are not necessarily assigned to consecutive workstations, the balancing potential is greater, as discussed in subsection 6.3.2. Therefore, it is logical to exclude rabbit chase and bucket brigades and continue with baton touch as the operating mode.

X.2 Assembly line balancing

Balancing the workload of the lever assembly process in a baton touch operation mode is similar to a type II assembly line balancing problem. Given the number of workstations, minimise the cycle time or maximise the output rate (Grzechca & Foulds, 2015). There is a large body of scientific literature covering the subject of assembly line balancing. It includes numerous problem-solving methods (e.g., heuristics) in a deterministic or stochastic setting. However, balancing the workload of the lever assembly is an exploratory study as assembly line balancing is not the main focus of this research. In addition, the number of workstations is only nine, and thus the solution space is small. Hence, the study does not formulate and solve a mathematical model. It uses the deterministic mean processing times per process step of the proof of concept (future state) to balance the workload.

The workload balancing started with the situation where two employees assemble levers, and the cycle time in the future state is minutes, determined in subsection 7.4.3. Then, each employee would ideally have a workload of minutes. However, Figure 7.11 revealed that the processing time of the first three assembly steps is about minutes. Note that the processing times of the first two assembly steps are each the sum of three workstation processing times. Table 6.1 lists the workstations per assembly step. So, combining two of these three assembly steps equals about minutes. Hence, the balancing line is minutes over the assembly steps, given in Figure X.1. However, combining the remaining assembly step (e.g., mounting the slide block) with the last two assembly steps results in more than minutes. Fortunately, there are some aspects to consider. The first is additional assembly time to press the bush bearings into the pivot block. Subsection 7.2.3 described the use of two processing times, one where the employees do and one where they do not encounter any issues with the bush bearings. In addition, it mentioned that the lever cycle times for the hypothesis testing consisted of the (longer) processing times with component quality issues. However, VMI initiated the process to improve the engineering fit between the two mating components. Thus,

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The design change offers the opportunity to adopt the processing times without any issues. It reduces the mean processing time of pressing the bush bearings into the pivot block by seconds to seconds.

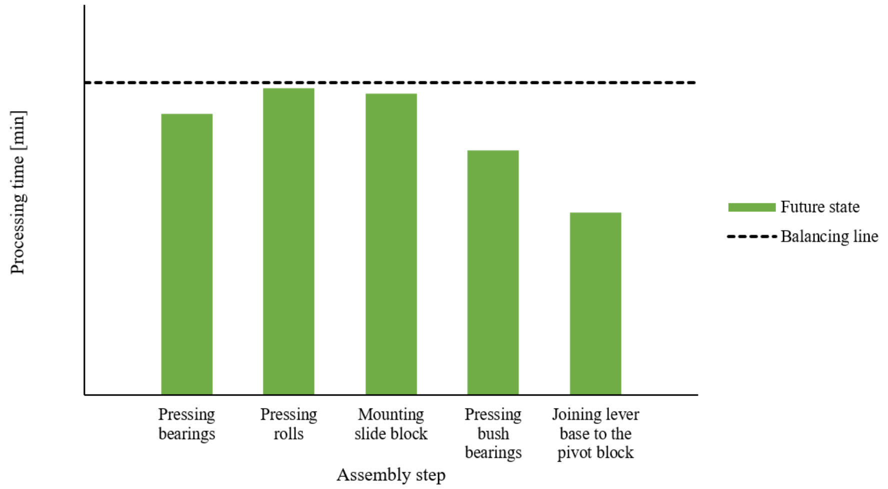
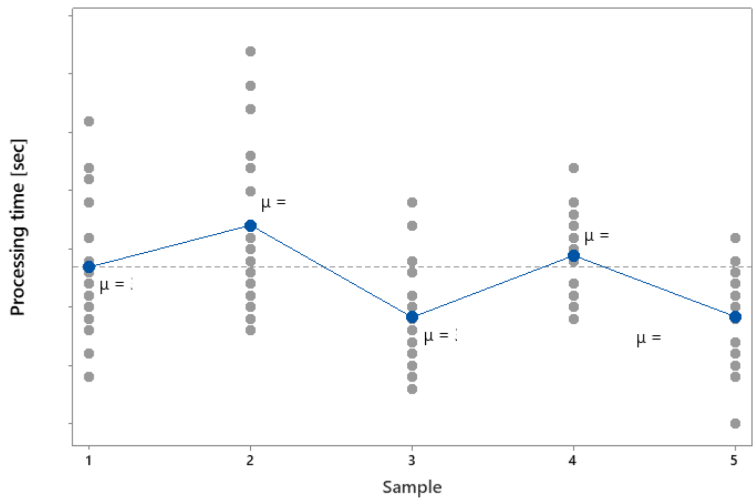


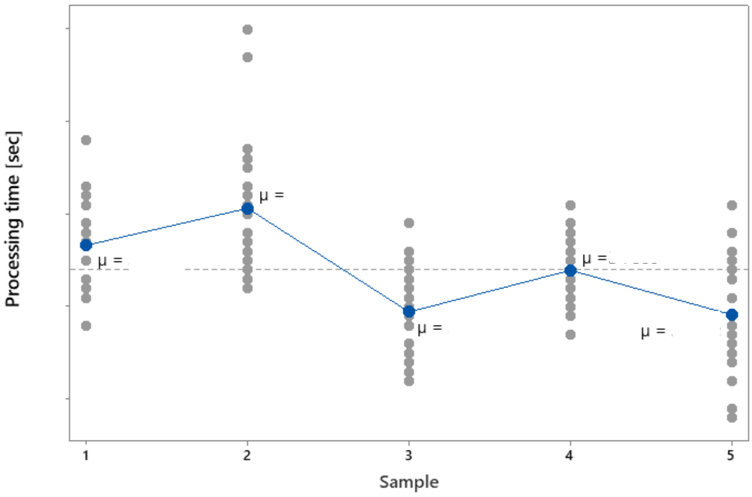
Figure X.1: Processing time per assembly step and balancing line of one minute.

The second aspect to consider is the continuation of the learning curve. As the two employees assembled more levers during the proof of concept, they became more familiar with the new process design. In particular, the new assembly methods for the last two assembly steps. Figure X.2 and Figure X.3 show the processing times for the assembly steps pressing the bush bearings into the pivot block and joining the lever base to the pivot block per sample, respectively. The sample numbers represent the employees, where the even numbers represent one employee and the odd numbers represent the other. Important to note that the processing times of pressing the bush bearings into the pivot block are the processing times without any assembly issues. Comparing the first sample with the last sample per employee for the fourth assembly step reveals the means decrease by and seconds for the odd and even employee, respectively. The decline in the means is and seconds for the odd and even employee in the other assembly step, respectively. If the mean of the last two samples replaces the mean of the five samples, the fourth assembly step reduces by seconds to seconds and the fifth assembly step by seconds to seconds.



Legend:
- Odd numbers employee 1
- Even numbers employee 2

Figure X.2: The mean processing time for pressing the bush bearings into the pivot block per sample per employee.



Legend:

- Odd numbers employee 1
- Even numbers employee 2

Figure X.3: The mean processing time for joining the lever base to the pivot block per sample per employee.

The third aspect to consider is that the proof of concept did not use industrial-grade fixtures, and the new assembly methods were prototypes. Therefore, when the process is an industrial-grade process, the processing times likely decrease even further. The fourth and fifth assembly steps benefit the most from the industrial-grade process. It will help reduce the variation in the processing times. Figure X.2 and Figure X.3 show there is still some relatively large variation in these processing times. Some of the variation is explainable. The fixture in the fourth assembly step had some damage, and the tooling of the fifth assembly step already needed strengthening during the proof of concept. The second and the third aspect combined result in a processing time reduction. It is hard to say how much this reduction is but a decrease of seconds per assembly step seems very reasonable.

The fourth aspect to consider is the use of the tuflok screws. Subsection 6.2.4 introduced the use of these screws to replace screws employees currently dip into adhesive. It mentioned that even if there is a minor financial loss, it does not outweigh the gain in safety since the adhesive is a hazardous substance. Hence, it is very likely that VMI will implement the tuflok screw in the near future. A conservative estimation of the processing time reduction is seconds per screw. Thus, the processing time of mounting the slide block to the lever reduces from seconds to seconds.

The last four paragraphs mentioned four aspects to consider in the lever assembly time. They result in an expected assembly time per lever of minutes, a decline of seconds. Then, each employee would ideally have a workload of minutes. Figure X.4 gives the processing times per assembly step. It includes the four mentioned aspects. Combining the mean processing times of the fourth and fifth assembly steps results in minutes. Given that it is slightly over the target balancing time of minutes, it is logical to combine these two assembly steps with the lowest processing time. The result is two options, the first and third assembly steps. They both have a mean processing time of seconds. The decisive criterion is walking distance. The list of requirements gives it should be as short as possible, listed in subsection 6.1.2. Figure X.5 illustrates the two options using the colours blue and black. The blue lines represent the first employee performing assembly steps one and two, and the other employee assembly steps three to five. The black lines are the first employee carrying out assembly steps one, four, and five, and the other employee assembly steps two and three. The employees cover in the blue option 12.4 meters whereas in the black option the distance is 14.5 meters. So, the workload balancing with two employees is employee one performs the first and second assembly step, and the second employee performs the third to fifth assembly step. Figure X.6 visualises the workload balancing, and there is only a minor balancing loss. The balancing loss is theoretically only seconds. However, the figure uses a balancing line of minutes to overcome the variation in processing times. The cycle time per lever with two employees in the process becomes minutes.

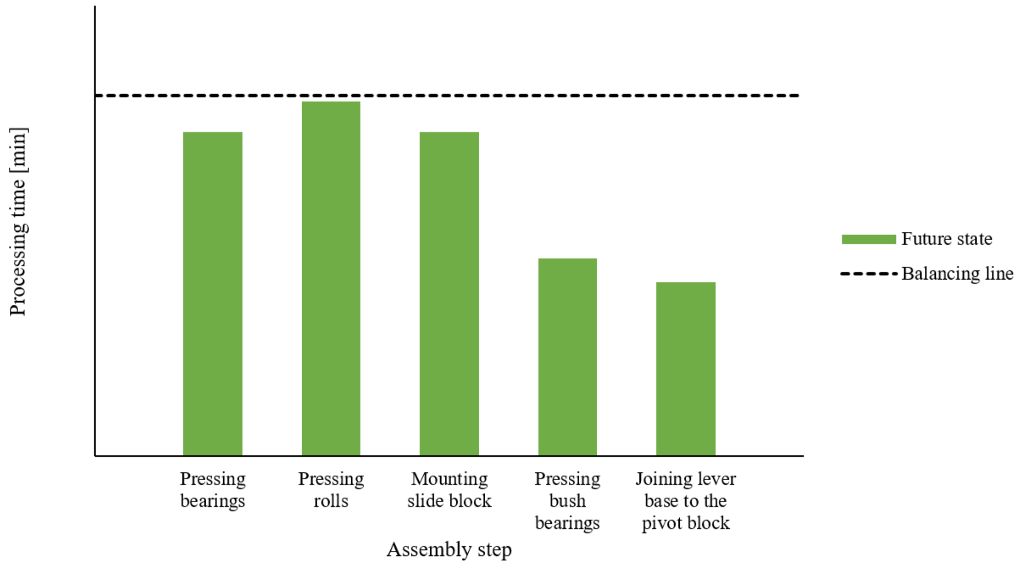
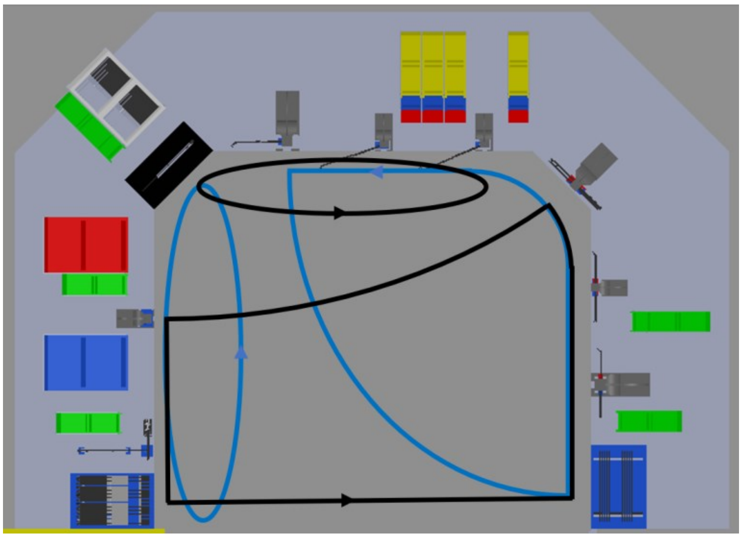


Figure X.4: Processing times per assembly step including the four considerations.



Legend:

- Blue lines:
  Employee 1 – Step 1 & 2
  Employee 2 – Step 3,4 & 5
- Black lines:
  Employee 1 – Step 1, 4 & 5
  Employee 2 – Step 2 & 3

Figure X.5: Two workload balancing options with two employees.

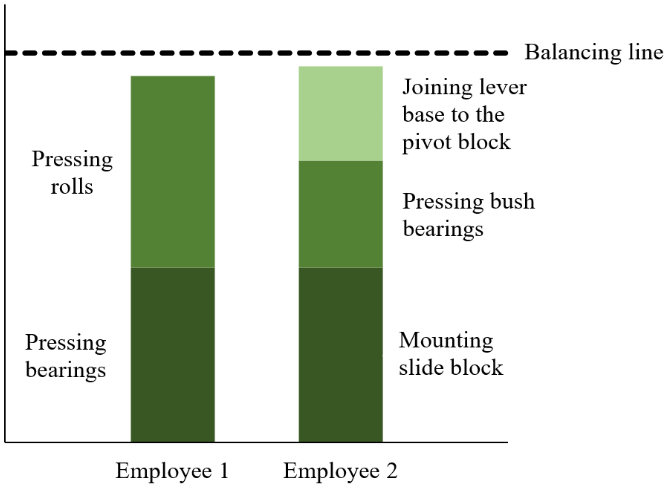


Figure X.6: Work balancing with two employees in the future state of the lever assembly process.

The presented distribution of assembly steps balances the workload very evenly over the two employees. Before continuing the workload balancing with three or more employees, it is relevant to discuss the capacity of the lever assembly process in the future state. For this purpose, the effective lever cycle time of minutes, determined in subsection 7.4.3, is used. It is equal to the output rate of standard levers per hour. Hence, one employee can assemble slightly more than thousand standard levers per year, as listed in Table X.1. Note that these rates do not include the decrease in cycle time due to the four mentioned considerations. The main purpose of Table X.1 is to give a proper indication of the new process capacity. In addition, when two employees assemble levers, the output rate is levers. An adjustment to include productivity loss due to increased output rate. Then the two employees can assemble over thousand standard levers per year. To place these process capacities in perspective, the current demand for all lever varieties is . The capacity of the new process design of the lever is with one employee 1.7 times and with two employees 3.3 times larger than the annual demand. It can easily handle further growth in the future. Furthermore, it indicates that further balancing of the workload with three or more employees is superfluous. In case of peak demand for levers, it is wise to let four employees assemble levers rather than three. Then, every employee has a workload of about minutes, and the balancing loss is seconds. The latter assumes a balancing target of minutes. A final remark, when four employees assemble levers, employees should frequently rotate in assembly tasks to prevent repetitive work. Otherwise, the dynamism of the one-piece-flow process, introduced with the new process design, is lost.

Table X.1: Future process capacity of the lever assembly process with one and two employees.

	Effective cycle time [min]	Output route				Annual demand	Capacity
		Hourly	Weekly	Monthly	Yearly		
1 employee							1.7
2 employees							3.3

Appendix Y Variation reduction

To showcase the variation reduction of the fourth level of the CIMM, we apply it to the lever cycle times of the proof of concept. For this purpose, we use the I-MR chart. An I-MR chart is a control chart that helps determine special cause variation. It is a combination of the two charts Individual and Moving Range chart that monitors the mean and spread of a process. Furthermore, it uses control limits, and when a data point is outside of the control limits, a special cause variation is determined (Theisens, 2017).

We split the 100 lever cycle times into the five separate subgroups of 20 as in the proof of concept. Then, we used the I-MR chart to determine any outliers in the 20 samples. Figure Y.1 shows the cycle times of the first 20 observations. It gives that sample number 18 is out of control since it is outside the control limits. We could trace the issue to the engineering fit between the bush bearings and the pivot block. Subsection 7.2.3 mentioned that if this problem arose during the proof of concept, we would record the lever involved and its consequences. Hence, we deducted the time lost from the original cycle time and used the I-MR chart again. Figure Y.2 gives the results and indicates that the seventh sample is out of control in the moving range chart. We repeated the described procedure since we knew the cause (i.e., the engineering fit between the bush bearings and the pivot block). Eventually, we corrected four data points in the first subgroup. Figure Y.3 gives the I-MR chart after those four corrections. Subsequently, we repeated the described procedure for the four other subgroups of 20 samples. We corrected 13 data points in total, and all 13 had the engineering fit between the bush bearings and the pivot block as cause origin. Figure Y.4 gives a graphical summary of the cycle times, including the 13 corrected values. The process variation has reduced to such a level that the cycle times follow a normal distribution. The p-value of the Anderson-darling test is higher than 0.05 if we adopt a 95% significance level. Furthermore, the skewness is relatively low, and the mean and median are almost equal, which are more characteristics indicating a normal distribution. Thus, by redesigning the engineering fit between the bush bearings and the pivot block, the production process design of the lever can already improve to such an extent that the cycle times follow a normal distribution.

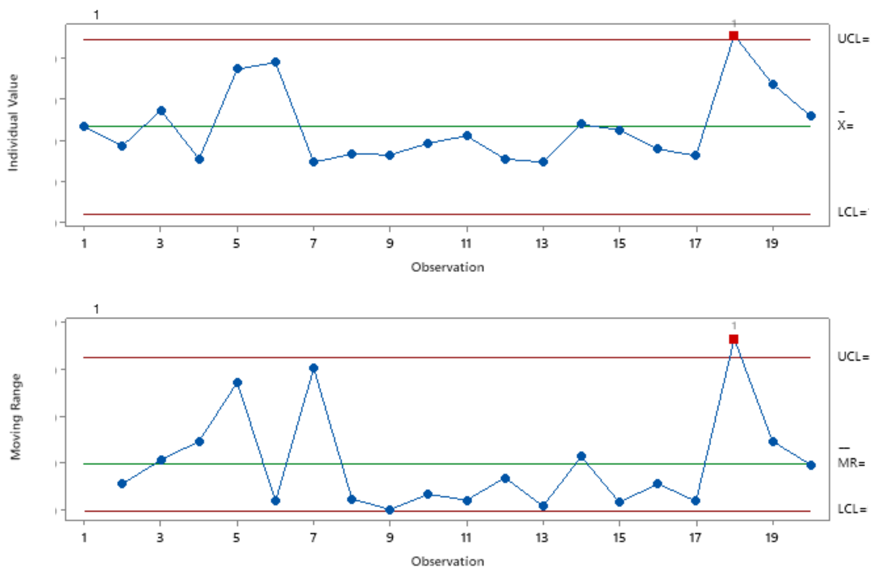


Figure Y.1: I-MR chart of the original cycle times of the first assembly session.

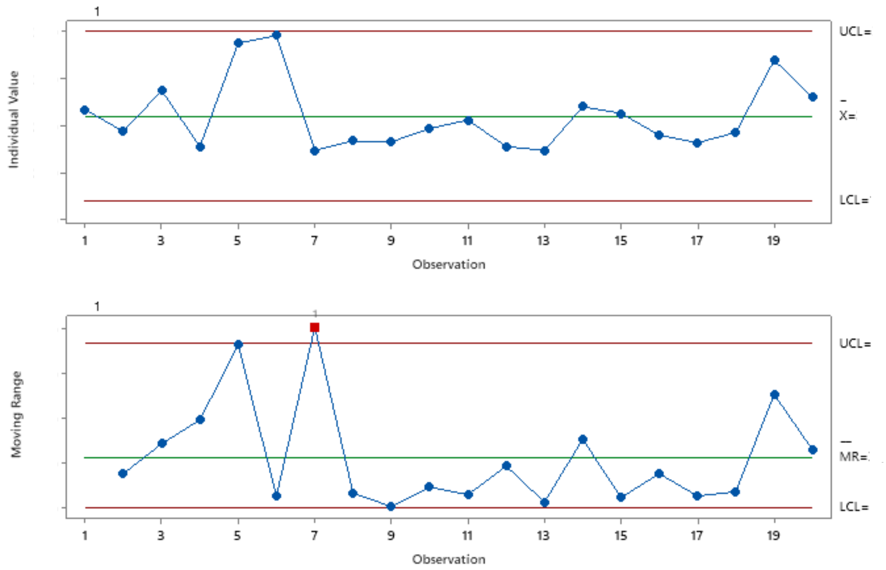


Figure Y.2: I-MR chart of the first assembly session after the first correction.

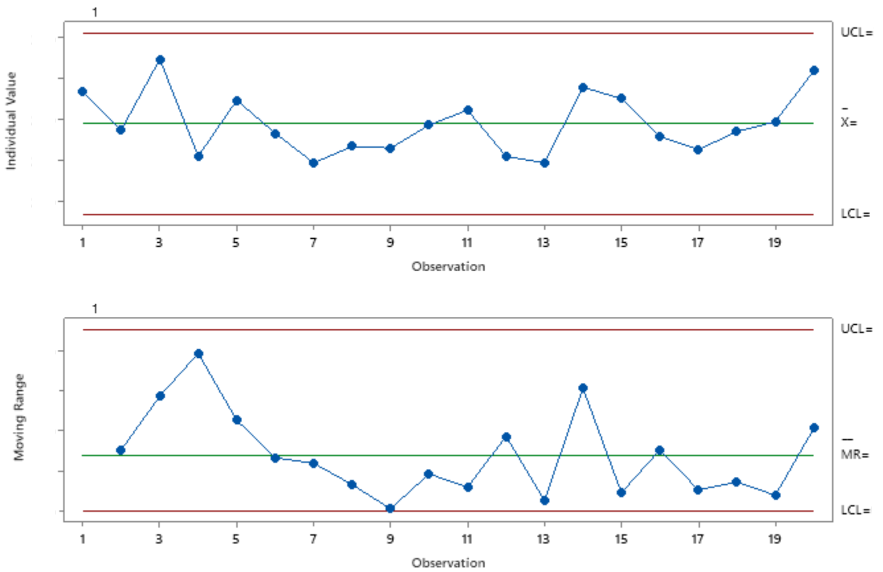


Figure Y.3: I-MR chart of the first assembly session after four data corrections.

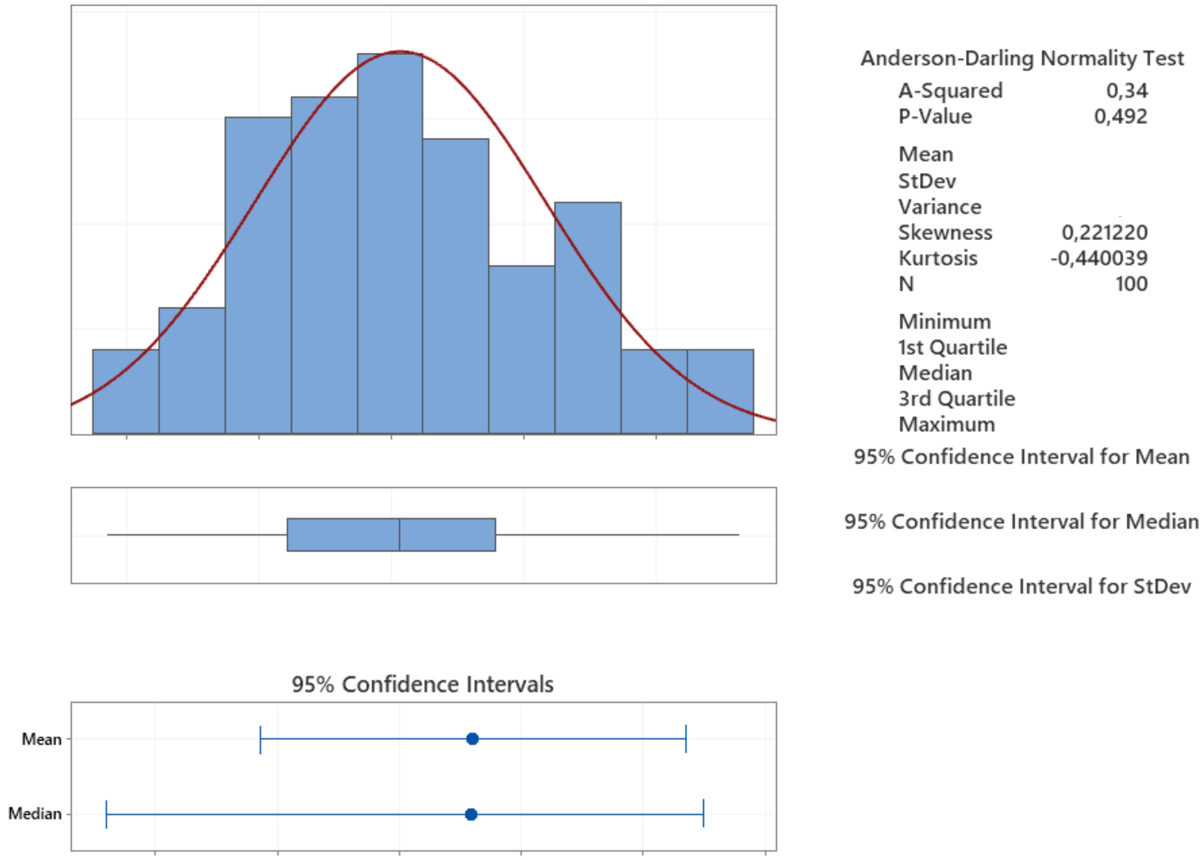


Figure Y.4: Graphical summary of the 100 lever cycle times after the correction of 13 values.

Appendix Z Cost-benefit analyses

To determine if an investment in the new process design of the lever is sound, we compare the total expected cost with the total expected benefit using a cost-benefit analysis. The cost-benefit analysis evaluates three scenarios:

- **Scenario 1:** Process design
- **Scenario 2:** Process design + pre-implementation activities engineering
- **Scenario 3:** Process design + pre-implementation activities engineering + design change slide block

The following three sections detail per scenario the costs, benefits, and ROI.

Z.1 Scenario 1

The first scenario is the process design of the lever, as presented in Chapter 6. It assumes that the situation is equal to the proof of concept, for example, no quality standards and no improvement of component quality. It only implements the proposed process design. The costs of the process equipment originate from potential suppliers. In addition, we consulted a multidisciplinary team for realistic estimation of the fixtures and pressing tools, for instance. We adopted the costs of man-hours from the implementation plan discussed in Section 8.1. The benefits originate from the future performance, presented in Section 7.4. For this purpose, we used the effective cycle time of minutes and deducted it from the minutes of the baseline performance. We multiplied the outcome by , the annual demand for levers, and € , the costs VMI incurs to employ someone in the sheltered workshop. The results are the savings in assembly time (i.e., hours) and assembly costs (i.e., €). The increase of the FTR-% yield savings in replacement components. Figure Z.1 overviews the costs, benefits, and ROI of the first scenario. It shows that the scenario is financially viable. It returns the € investment in months because the new process design saves € annually.

Non-recurring costs	Annual benefits	ROI
Process equipment	**Man-hours**	years
Workbenches	Cycle time reduction	months
Manuel press (HK 800)		
Manuel press (HK 1700)	**Materials**	
Dowel press	Replacement components	
Fixtures		
Pressing tools		
Component bins + lids (3L)		
Lever bins + supports		
Bin flow rack (2-level)		
Bin flow rack (3-level)		
Bin flow rack (VMI-bin)		
Flow rack		
Table of Sin		
Man-hours		
Industrialisation process		
Skill matrix		
Implementation information and material streams		
Implementatie process design		
Unforeseen		
Total	**Total**	

Figure Z.1: Overview of the non-recurring costs, annual benefits, and ROI of the first scenario.

Z.2 Scenario 2

The second scenario is the first scenario with the addition of the pre-implementation activities of engineering. These activities define the quality standards, review two engineering fits, and redesign the engineering fit between the bush bearings and the pivot block. The additional costs are the man-hours listed in subsection 8.1.1 and the material costs to order a test batch of 90 pivot blocks to review the redesign. The benefits are an effective cycle time reduced by seconds to minutes per lever. Moreover, the FTR-% increases by % because engineering has reviewed the two engineering fits and has redesigned the engineering fit between the bush bearings and the pivot block. Hence, it results in it fewer costs for replacement components. Figure Z.2 overviews the costs, benefits, and ROI of the second scenario. It lists non-recurring costs of € and annual benefits of € . Therefore, the second scenario is also financially viable since its ROI is months. Slightly higher than the first scenario, but the scenario yields in the long term far higher savings.

Non-recurring costs	Annual benefits	ROI
Process equipment	**Man-hours**	years
Workbenches	Cycle time reduction	months
Manuel press (HK 800)		
Manuel press (HK 1700)	**Materials**	
Dowel press	Replacement components	
Fixtures		
Pressing tools		
Component bins + lids (3L)		
Lever bins + supports		
Bin flow rack (2-level)		
Bin flow rack (3-level)		
Bin flow rack (VMI-bin)		
Flow rack		
Table of Sin		
Man-hours		
Defining quality standards		
Review two engineering fits		
Redesign engineering fit pivot block/bush bearings		
Industrialisation process		
Skill matrix		
Implementation information and material streams		
Implementatie process design		
Materials		
Redesign engineering fit pivot block/bush bearings		
Unforeseen		
Total	**Total**	

Figure Z.2: Overview of the non-recurring costs, annual benefits, and ROI of the second scenario.

Z.3 Scenario 3

The second scenario is the second scenario with the addition of the design change of the slide block. The additional costs are the man-hours listed in subsection 8.1.3 and the material costs to order a test batch of 90 slide blocks for the endurance test. The benefits are an effective cycle time reduced by seconds to minutes per lever. In addition, in the case of technically viable design, two components become redundant, discussed in subsection 6.2.4, and yield additional savings. Figure Z.3 overviews the costs, benefits, and ROI of the third scenario. It shows that the third scenario is financially viable. It returns the € investment in months, given the annual savings of € . It shows that the ROI only increases by months, and VMI can potentially save an enormous amount of money in the long term.

Non-recurring costs	Annual benefits	ROI
Process equipment	**Man-hours**	years
Workbenches	Cycle time reduction	months
Manuel press (HK 800)		
Manuel press (HK 1700)	**Materials**	
Dowel press	Replacement components	
Fixtures	Design change slide block	
Pressing tools		
Component bins + lids (3L)		
Lever bins + supports		
Bin flow rack (2-level)		
Bin flow rack (3-level)		
Bin flow rack (VMI-bin)		
Flow rack		
Table of Sin		
Man-hours		
Defining quality standards		
Review two engineering fits		
Redesign engineering fit pivot block/bush bearings		
Industrialisation process		
Skill matrix		
Implementation information and material streams		
Implementatie process design		
Redesign slide block		
Materials		
Redesign engineering fit pivot block/bush bearings		
Redesign slide block		
Unforeseen		
Total	**Total**	

Figure Z.3: Overview of the non-recurring costs, annual benefits, and ROI of the third scenario.