UNIVERSITY OF TWENTE.

VDL ETG ALMELO

# SELECTION OF AUTOMATION OPPORTUNITIES IN HIGH-TECH MANUFACTURING PROCESSES

## Bachelor Thesis

*Luka Catharina Beers*

***First supervisor university***
*Dr. ir. J.M.J Schutten*

***Second supervisor university***
*Ir. I.M.W. Schrader*

***Company supervisor***
*Ir. S. de Vries*

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# Management summary

The T&D department at VDL ETG wants to optimize their manufacturing processes through automation, considering not only quality, but also other factors such as cost optimization and decreased labour hours. To make informed and impactful decisions, VDL needs a method that provides objective insights into the full range of process optimization opportunities through automation.

After identifying the problem and scope of this research, we begin by consulting the literature. In the theoretical framework we describe important optimization methods, the impact of process variability on automation and Frohm's Level of automation (LoA) scale, which categorizes the degree of automation. Additionally, we identify three phases in the decision-making process that align with our research approach: exploration, analysis, and decision-making. The exploration phase involves describing the current situation at VDL and their production process. In the analysis phase we focus on developing a method to evaluate different automation opportunities and provide recommendations to VDL.

We develop a tool for VDL to determine which tasks in the high-tech, low-volume manufacturing process should be optimised with automation. This tool can be applied to various high-tech manufacturing processes. The tool includes a comparison of the minimum, current and maximal LoA. These levels are assigned by VDL with the DYNAMO method, which is a method specifically for manufacturing processes to determine the LoA. The tool also includes an analysis on potential yield in production costs, based on cycle time reduction and utilization. Additionally, we develop a process variability framework which indicates the maximum economic viable LoA in the tool. Based on these factors the tool recommends a LoA for each task in a high-tech manufacturing process at VDL ETG.

In our research, we apply the tool to two specific tasks in one manufacturing process. One task yielded the expected outcome, while the other required minor adjustments to the variability framework. We recommend fine-tuning the tool, including the variability framework, and applying it to additional tasks for further validation. Additionally, before automation, we highlight the importance of reducing waste in the manufacturing process and integrating all improvement methodologies in continuous improvement efforts.

# Preface

Dear reader,

This thesis is written as final part of my bachelor's degree in Industrial Engineering and Management at the University of Twente. Throughout my research, I have had the privilege of working with VDL ETG Almelo, an experience that has been invaluable to my academic and professional growth.

During my time at VDL, I made significant strides in conducting research, and I want to express my gratitude to everyone who warmly welcomed and supported me on this journey. The enthusiasm of employees, their guidance within this large organization and their willingness to answer my questions and provide feedback, have been remarkable. The operators in the factory were especially supportive and willing to help.

I would like to extend a special thanks to my supervisor at VDL, Sybren de Vries, for his readiness to address my questions, provide interesting insights and engage in discussions that greatly enriched my research.

I would also like to thank my academic supervisor Marco Schutten, for his consistent feedback and thought-provoking comments, which have been instrumental in the development of this thesis.

Finally, I am also grateful for my second supervisor, Ieke Schrager, who took the time to provide extra feedback and greatly contributed to the completion of this research.

Thank you all for your support and encouragement.

Sincerely,

Luka Beers

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# Abbreviations

| | |
|---|---|
| AHP | Analytic Hierarchy Process |
| CIP | Continuous Improvement Process |
| ETG | Enabling Technologies Group |
| I&C | Information & Control |
| KPIs | Key Performance Indicators |
| LoA | Level of Automation |
| M&E | Mechanical & Equipment |
| OEM | Original Equipment Manufacturing |
| QLTC | Quality, Lead time, Technique and Costs |
| ROI | Return on investment |
| SLR | Systematic Literature Review |
| T&D | Technology and Development |
| VDL | Van der Leegte |
| WIP | Work In Process |

# 1 Introduction

This chapter explains the purpose of the research and the way it is conducted. Section 1.1 introduces the company, product and topic of our research. Subsequently, we discuss the problem in Section 1.2. In Section 1.3 we describe the problem solving approach.

## 1.1 Company description

Our research is conducted for Van der Leegte Enabling Technologies Group (VDL ETG), a company we introduce in Section 1.1.1. In Section 1.1.2 we introduce the manufacturing process our research focusses on and in Section 1.1.3 we introduce the main topic of our research.

### 1.1.1 VDL ETG

VDL ETG is a part of VDL Groep, which is a Dutch family-owned group. The group encompasses more than 100 closely cooperating operating companies, spread over 19 countries operating in Hightech, Mobility, Energy, Infratech and Foodtech.

VDL ETG is a top-tier design and contract manufacturing partner with global operations. Customers are Original Equipment Manufacturing (OEM) companies that play a leading role in the production of high-tech equipment and use advanced production lines. Through collaboration with VDL ETG, numerous OEMs have successfully focused on their core technology while entrusting VDL ETG as their partner to handle the remaining innovation. VDL ETG operates in various markets such as the Medical and Solar industries, with our research focused on the Semiconductor industry.

Our research is performed for the Technology & Development (T&D) department of VDL ETG Almelo. The T&D department supports and works together with the factory. The department mainly focusses on supporting and improving the existing manufacturing processes and designing new manufacturing processes, when needed. Their expert knowledge is used for tooling developments, feasibility studies, or design changes. Our research originates from one of the projects within the T&D department: the Manufacturing Development project. This project is responsible for improving processes focusing on innovation (introducing new production methods), optimisation (improving efficiency by changing product design) and automation (reducing manual labour).

### 1.1.2 About the case product

Due to the confidentiality of the product, the product is now referred to as ‘product X’. Our research focusses on the manufacturing process of product X, which is part of semiconductor production machines. These machines are highly sensitive, requiring very precise and clean manufacturing, making product X a complex and expensive, high-tech product. The low volume manufacturing line is highly manual, using foremost handheld tools.

### 1.1.3 Automation

Companies with small scale manufacturing lines are often hesitant to invest in automation. The large investments involved, coupled with bad economies of scale, make it riskier for the investment to pay off. In recent years, new types of automation technologies that are more flexible and easier to program have emerged, proving to be more suitable and cost-effective for small batch manufacturing processes (Löfving et al., 2018). Resulting in a growing interest among businesses in acquiring knowledge and investing in automation for these operations (Löfving et al., 2023).

Embracing automation investments presents opportunities for competitiveness and profit enhancement. Companies can unlock benefits including improved productivity, quality, ergonomics and cost reduction in manufacturing processes. Additionally, automation can also optimise operations by addressing factors such as space requirements, flexibility, and employee dependency (Löfving et al., 2020). For example, VDL currently addresses employee dependency and production capacity by hiring more employees. However, this approach leads to high labour costs and could be more effectively managed through automation.

## 1.2 Problem identification

Section 1.2.1 introduces the chosen problem at VDL. In Section 1.2.2, we identify the root cause of the problem by creating a problem cluster.

### 1.2.1 Action problem

An action problem is the perceived discrepancy between desired norm and the current reality (Heerkens & van Winden, 2017). The action problem of our research is that the T&D department at VDL ETG struggles in selecting automation opportunities to optimise the manufacturing process of product X. It is beneficial for companies to make informed and systematic decisions, as stated by Salim et al. (2020), as such investments in automation are more likely to yield positive outcomes. Currently, VDL's investment decisions rely on experience and opinion, with the primary focus on improving product quality. While this is an important goal, a systematic analysis method can potentially realize greater benefits, by providing objective insights into automation opportunities. Such insights would enable more impactful investments, leading to reduced production costs, minimized employee dependency, and improved ergonomics and manufacturing flexibility.

### 1.2.2 Core problem and problem cluster

A core problem is a problem that can be influenced to change the reality of the action problem (Heerkens & van Winden, 2017). By creating a problem cluster (Figure 1), we can identify core problems that, if addressed, can enhance VDL's ability to gain objective insights into process optimisation and better evaluate the potential benefits of automation investments. As shown in Figure 1 the main cause of the lack of insight into automation opportunities is the general lack of insight into process optimisation opportunities. Without this insight, the potential benefits of automation investments become uncertain. The lack of objective insight in process optimisation can be traced back to three core problems.

First, the company's main priority is ensuring product quality, since that is the primary concern for their client. Management has shown little interest in analysing process optimisation opportunities by creating a systematic method or mapping the manufacturing process, even though these approaches can be effective for identifying optimisation opportunities. This reactive approach means that as long as the product meets the client's requirements, there is little incentive to make changes.

Secondly, the unique nature of each project makes it difficult to obtain consistent data. Without sufficient availability of data, as each optimisation project varies and no systematic approach is utilized at VDL to gather data, leveraging data-driven insights becomes challenging.

Finally, our selected core problem is that VDL does not have a method or tool available to objectively analyse process optimisation opportunities, while considering all automation benefits. This makes it difficult to identify improvement areas and objectively select automation investments.

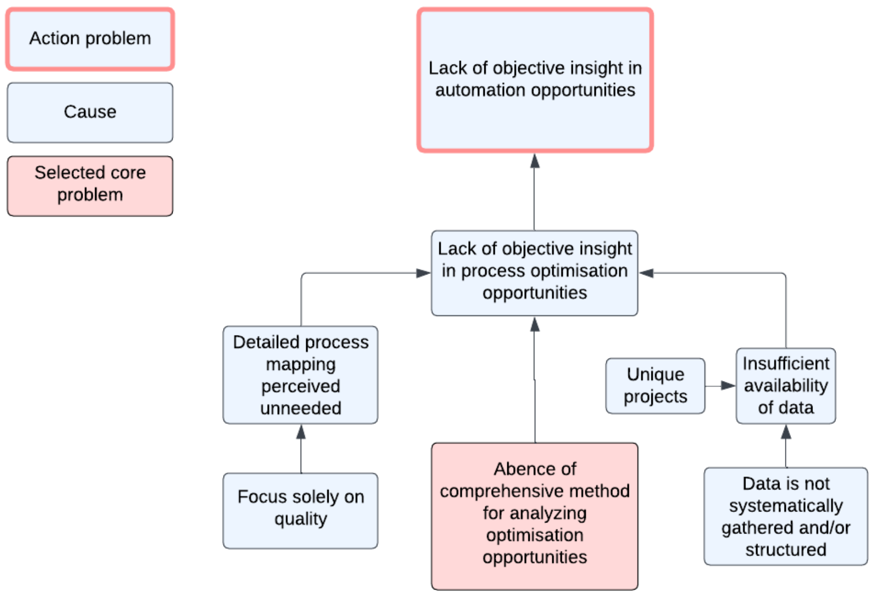



Figure 1: Problem cluster

## 1.3 Problem solving approach

In Section 1.3.1, we explain the research question and sub-questions, which divide the research into manageable parts. Furthermore we provide a description of the deliverable in Section 1.3.2 and a description of the scope of the research in Section 1.3.3.

### 1.3.1 Research question and sub questions

To solve the core problem we create the following main research question:

“How can VDL determine which tasks in the high-tech, low-volume manufacturing and assembly process should be optimised with automation?”

We break the main research question down into smaller parts with three research questions. Research question 1 aims to build a comprehensive understanding of existing literature on optimisation through automation investments and is addressed in Chapter 2. Sub question 1.1 explores available automation decision-making strategies that can be applied to the manufacturing process of product X. Sub question 1.2 explores optimisation and how we can measure optimisation. Sub question 1.3 focuses on non-economic factors that influence the selection of automation opportunities, while Sub question 1.4 explores how we can determine the economic impact of automation opportunities.

1. What literature is available on optimisation through automation in manufacturing processes?
   1.1. What decision strategies are available for implementing automation in high-tech, small scale manufacturing lines?
   1.2. What are effective methods to determine process optimisation?
   1.3. How can the suitability of automation investment opportunities be objectively assed to facilitate decision-making?
   1.4. How can the expected economic impacts of potential investment opportunities be determined?

Research question 2 aims to understand the current situation at VDL and is addressed in Chapter 3. The investigation of this question involves qualitative and quantitative data from the company’s data base. Additionally we gather qualitative data during meetings with managers and engineers, conversations with employees, and observations made in the manufacturing process of product X. To address Sub question 2.1, we identify VDL's strategy to ensure alignment with our automation selection method. Sub question 2.2 focuses on gaining a clear understanding of the current manufacturing process and its specific tasks. Finally, Sub question 2.3 assesses the potential for automation within the manufacturing process of product X.

2. What is the current situation at VDL?
   2.1. What are the goals and objectives of VDL’s manufacturing and assembly operations?
   2.2. What is the current manufacturing process of product X?
   2.3. Which tasks can be automated in the manufacturing process of product X?

Research question 3 aims to leverage the knowledge and insights we gather by answering Research question 1 and 2. The goal is to develop a suitable approach for decision-making regarding automation investments. Since not all automation benefits can be easily expressed in economic terms, we divided Research question 3 into sub-questions. In Chapter 4 we develop a framework that aims to measure the impact of automation opportunities, which we use in Chapter 5 to answer Sub questions 3.1 and 3.2.

3. Which decision-making approaches suit best to facilitate decision-making for the manufacturing process of product X?
   3.1. How can we determine the non-economic impact of automation opportunities for VDL?
   3.2. How can we determine the economic impact of automation opportunities for VDL?

### 1.3.2 Deliverable

The company needs a new approach in deciding where to automate in the high-tech, low-volume manufacturing and assembly line of product X. An approach that facilitates informed and systematic decision-making for automation investments. This approach should consider multiple factors, based on the company's perspective and aim to optimise their process.

### 1.3.3 Scope

The duration of the project is approximately 10 weeks, but there are many things that can be considered in the decision-making of new technologies investments in a manufacturing process. To maintain the integrity of the research, this time constraint causes the need of setting boundaries.

The focus lies on the chosen core problem of finding a structured approach in investment decision-making of automation. Other factors that influence the manufacturing process such as supply chain inefficiencies are left out. Additionally, only factors considered important by the perspective of the company are considered in the objective analysis of automation opportunities.

Lastly, the analysis on investment decisions needs to be useful for automation investments until 2030, which is around five years. Later than that year, the demand of the product is too unpredictable, to know if investments are useful or not.

# 2 Theoretical Framework

This chapter delves into the available literature on automation investment decision-making to optimise production and assembly processes, addressing Research question 1:

"What literature is available on optimisation through automation in manufacturing processes?"

Section 2.1 describes the findings of a Systematic Literature Review (SLR), which explores the existing literature on automation decision-making strategies. Section 2.2 discusses process optimisation and identifies key performance indicators (KPIs) used to measure it. Section 2.3 examines the suitability of different investment opportunities. Finally, Section 2.4 evaluates the economic impact of these investments.

## 2.1 Automation road mapping

We conduct a systematic literature review (SLR) in Appendix A, addressing Sub question 1.1:

"What decision strategies are available for implementing automation in high-tech, small scale manufacturing lines?"

In this chapter we conclude the findings of the SLR. Section 2.1.1 explores road mapping, followed by Section 2.1.2, where the general road mapping strategy is described. In Section 2.1.3, we conclude that there is a gap in the literature when it comes to a suitable approach for automating high-tech, small-scale manufacturing lines.

### 2.1.1 Road mapping

When investing without clear objectives and structure, automating can increase complexity and costs. For example, any task that does not add value to the final product, could be called waste and automating waste is inefficient (Löfving et al., 2020). Without clear objectives and structure, the company has no clear view on waste in the manufacturing process and could thereby diminish the impact of investments. Currently automation investments decisions in small scale production processes are often based on assumptions, but the influence of those decisions tend to be large on the whole process and competitiveness (Löfving et al., 2023).

A roadmap is a strategic planning tool that helps organizations enhance technology planning and coordination. It serves as a structured plan that outlines the steps, objectives and goals related to technology and development initiatives. A key function of a roadmap is to provide valuable information and insights on identifying technology investment opportunities. Hence the development of a roadmap, which is grounded in objectivity and guides companies through the decision-making process, can prove highly beneficial (Garcia & Bray, 1997).

While a generic roadmap is helpful, a roadmap needs to be tailored to the objectives and goals of the company, which the decisions depend on. For the creation of an effective roadmap stakeholders need to be willing to invest time and energy in the iterative process of data collection and analysis

(Phaal et al., 2004). Keeping the roadmap alive and up to date after creation is often a big struggle within companies. Roadmapping is not a one-time activity, but a continuous process that adapts along with the developments in an organization. It is not a static approach, but a dynamic approach that is continuously improved and updated as circumstances change (Groenveld, 2007).

### 2.1.2 Roadmapping phases

Even though roadmaps should be tailored to the companies requirements, the creation of the roadmap and steps can be generic. We identify three common phases that suggest a level of generality in literature (Garcia & Bray, 1997; Hummel, 2019; Löfving et al., 2023). These present the fundamental building blocks in many technology decision-making approaches, despite the differences in the overall frameworks.

- Exploration phase:

In this phase the automation opportunities in the manufacturing process are explored. The company must be ready to automate, requiring stakeholder readiness to invest time and effort in the automation roadmap and an evaluation of current process performance. Key questions by Löfving et al. (2023) include: is the company ready to automate, and what can be automated? Identification of automation opportunities in the process is necessary to assess whether there are viable opportunities. A detailed description of the processes, highlighting all potential automation opportunities, is advised to ensure a comprehensive view and to avoid missing any potential enhancements. Hummel (2019) makes these questions more practical by exploring the current process through a risk analysis and assigning the Level of Automation (Section 2.3.1). The report of Garcia & Bray (1997) overlaps by also exploring stakeholder investment, investment alternatives, the current process and company goals and objectives.

- Analysis phase:

In this phase the different automation opportunities and manufacturing tasks need to be analysed. Key questions by Löfving et al. (2023) include: is it suitable and profitable to automate? Hummel (2019) analyses solutions gathered in the exploration phase and calculates the economic impact of automation opportunities. Garcia & Bray (1997) also utilize the gathered information in the exploration phase to analyse opportunities and provide recommendations to the company in a report.

- Decision phase:

In the last phase the company needs to decide on investments based on the recommendations from the analysis phase and implement the chosen one(s) (Garcia & Bray, 1997; Hummel, 2019; Löfving et al., 2023). Additionally, Garcia & Bray (1997) include a follow-up activity, where the roadmap is reviewed and updated.

### 2.1.3 Gap

In conclusion, the SLR shows the value of a roadmap and factors to take into account when creating a roadmap. Including phases which describe valuable building blocks for the decision-making process. However, there is no roadmap available that is already completely applicable to aid the company in the decision-making process or the practical approach on how to create this tailored roadmap. The objective analysis included in the roadmap needs to consider multiple factors depending on the preferences of the company.

## 2.2 Process optimisation

Optimisation is identified as a key strategy for improving processes. To determine the impact of automation opportunities on process optimisation, it is crucial to understand the concept of optimisation and how to measure it effectively. Additionally, it is important for determining whether a manufacturing process is already optimised, as discussed in Section 2.1.1 this is crucial to avoid automating waste. In this section we address Sub question 1.2:

> "What are effective methods to determine process optimisation?"

To answer Sub question 1.2 we first explore optimisation (Section 2.2.1) and improvement methods (Section 2.2.2). Subsequently we address the underlying theories of process optimisation (Section 2.2.3) and in the final section (Section 2.2.4) we explore appropriate metrics to measure process optimisation in the manufacturing process of product X.

### 2.2.1 Optimisation

The definition of optimisation is making something (such as a design, system, or decision) as good or effective as possible. In the nineteenth century, first steps to improve efficiency in production processes where taken. From there on many optimisation methods have emerged and are available in literature. Popular methods are for example, Kaizen, Six Sigma, Lean, Business Reengineering and Agile methods. Often these methods have overlapping key values, because the different entrepreneurs that designed these methods were inspired by each other (Hofmann, 2021). Not every method is applicable to every situation. According to Hofmann (2021), the selection of the optimal optimisation approach should be guided by an assessment of two key factors: complexity of the problem and comparison of the expected costs and benefits.

### 2.2.2 Improvement methods

#### *Continuous Improvement Process*

A foundational improvement method is the Continuous Improvement Process (CIP). The key factor to success in this method is the mindset, where optimisation should be seen as iterative process rather than a one-time exercise.

### Kaizen

After CIP, the Kaizen method emerged, which is focused on eliminating Muda: actual waste, Mura: inequality and Muri: overburdening. Kaizen meaning “Change for the better” in Japanese, stresses the importance of teamwork, by aiming to include employees form multiple levels in the organization in the optimisation process (Hofmann, 2021).

### Lean

Kaizen is considered to be the foundation for Lean management. The goal of Lean management is to maximize value and eliminate waste, by optimally coordinating work processes. Lean manufacturing recognizes eight types of wastes: overproduction, wait time, transportation, processing, inventory, excess motions, non-used talent and defects (Taghizadegan, 2006). The strategy that targets these wastes is defined as the 7 Lean principles (Hopp & Spearman, 2008):

1. Throughput rate = Demand
2. Full utilization of all equipment
3. Zero lead time to the customer
4. No late orders
5. Perfect quality
6. Zero raw material and zero finished goods inventory
7. Minimum work in process (WIP)

### Six Sigma

Building on Kaizen, there was the need for a more concrete, measurable method, leading to the creation of the Six Sigma approach. This method focusses on identifying defects and eliminating them (Taghizadegan, 2006). In this method the DMAIC cycle is used for existing processes, which stands for Define, Measure, Analyse, Improve and Control as depicted in Figure 2. The cycle emphasizes statistically measurable data for process improvement and control (Pugna et al., 2016). Additionally Lean and Six Sigma are often combined in management as Lean Six Sigma.


Figure 2: Six Sigma DMAIC cycle (LeanSixSigmaGroep, n.d.)

### 5S method

Another prominent method is the 5S method, which aligns with the ‘Muda’ principle of the Kaizen method. By systematically implementing these 5S steps, organizations can effectively identify and eliminate the eight wastes from Lean. The five steps are as follows:

1. Seiri (Sort): Distinguish necessary items from unnecessary ones and remove the latter. For example, tools can be ordered on how often employees use them (every minute, hour, day, month). If an item is used once a year or less one can ask itself: is it really necessary?
2. Seiton (Set in order): Organize remaining items in a logical, efficient manner. For example, the distance a tool should have to the employee in a workplace can be determined by how often the employee uses the tool.
3. Seiso (Shine): Maintain a clean, orderly work environment.
4. Seiketsu (Standardize): Establish consistent procedures and best practices.
5. Shitsuke (Sustain): Foster a culture of discipline to uphold the 5S steps (LeanSixSigmaGroep, n.d.).

#### *Information Technology*

Information Technology (IT) optimises business processes by providing advanced tools that complement methodologies such as Six Sigma and Lean. According to Ibrahim and Kumar (2024), integrating Lean Six Sigma with Industry 4.0 technologies (e.g., modelling, AI, big data analytics, automation, industrial robots, and smart sensors) is crucial for competitiveness, enabling precise data analysis, visualization and process variation identification. Six Sigma tools (e.g., statistical analysis, quality tools, multi-criteria decision-making methods) can effectively be applied to investment selection processes (Ibrahim & Kumar, 2024), further detailed in Section 2.3. Additionally, Ibrahim & Kumar (2024) conclude that predictive strategies in manufacturing, such as modelling and simulation, are key for cost optimisation.

According to Powers et al. (2003), the advantages of modelling a project selection situation, as with any decision under uncertainty, are significant. It reduces guesswork and the influence of personal opinion. The output can provide valuable information with several benefits:

- Risk-Sensitive Analysis: Offers a statistical basis to analyse available project alternatives considering risk.
- Confidence in Outcomes: Specifies the confidence in expected outcomes, expressed as probabilities.
- Effective Communication: Serves as a powerful communication tool that clearly expresses the range of outcomes and associated risks (Powers et al., 2003).

However, there are disadvantages to modelling and simulation. It requires an enormous amount of data that must be constantly maintained, and the model does not always account for variability, leading to potential discrepancies between predicted and actual behaviour. Additionally, because there is no general understanding of when a given rule works well, finding a solution can be a trial-and-error process.

Finally, a thorough understanding of the underlying theory in optimization methods is essential for designing an effective model before implementing changes. In Section 2.2.3 we develop this understanding through factory physics, which provides the theoretical foundation for optimization methods, enabling us to better analyse and implement changes in manufacturing processes.

### 2.2.3 Factory physics

The major trends, Six Sigma, Lean, and IT provide valuable methods and tools to drive organizational enhancements systematically. However, these approaches often lack a comprehensive scientific framework to fully understand underlying manufacturing operations. Therefore, factory physics becomes important, which explores the relationships among variability, WIP, cycle time, utilization and more.

#### *Variability*

Variability encompasses anything that deviates from the norm. Variability is caused by natural factors, random outages, setups, operator availability and rework. Often variability is caused by the mere fact of operators being humans. Internal (age, gender, motivation, relationships, education) and external (work environment, time, space constraints) factors influence this variability. Social and organizational factors can further influence human variability (Angel, 2016). Automation can enhance a standardized process and diminish the inevitable human factor of variability, such as human-error or human availability issues (Goh et al., 2020).

Variability is not always bad, as Table 1 also shows examples of good variability. Henry Ford's strategy of reducing variability and eliminating 'Muda' (waste) led to success, but eventually, his rigid approach resulted in a loss of market share. Competitors who embraced 'good' variability, such as product variety and technological change, were able to increase their profit despite the additional costs (Hopp & Spearman, 2008).

Table 1: Good and Bad variability (Hopp & Spearman, 2008)

| Bad | Example | Good | Example |
|---|---|---|---|
| **Planned outages** | Setups | **Product variety** | Different colours |
| **Unplanned outages** | Machine failures | **Technological change** | Hard to enter market for competitors because rapid evolving technologies |
| **Quality problems** | Yield loss and rework | **Demand variability** | Demand of product X rapidly changes, however VDL makes sure they meet the demand, creating a strong market position |
| **Operator variation** | Skill differences | | |
| **Inadequate design** | Engineering changes | | |

Identifying the variabilities in a process is crucial for understanding the impact of automation. Variability can be inherent in the process or introduced by humans. Process variability refers to the natural and unavoidable fluctuations that occur in the production system. Researchers conclude that variability is not only introduced but also often addressed by operators. They use their skills to adapt to variability, meeting product and process specifications. For example, if an operator discovers that a drying step takes ten minutes instead of the five minutes specified in the guidelines, they adjust accordingly (Angel, 2016; Goh et al., 2020). Angel (2016) divides variability introduced by humans into three categories. If the third category of human variability is identified, the company should address it for process improvement.

1) Variability that is introduced by operators but its impact in the final product is neglected.
2) Variability introduced by operators that is corrected during the process, having no impact on outcomes.
3) Variability that is introduced by operators that affects the final outputs.

### *WIP and cycle time*

As mentioned in Section 2.2.2, one Lean principle is to keep a minimal WIP. WIP is the number of unfinished parts or products released into the production process. In general, the fraction of WIP that is actually being moved or processed is small, less than ten percent (Hopp & Spearman, 2008). To understand the relationship between WIP and cycle time we use an expression of Little's Law by Hopp & Spearman (2008):

$$Cycle\ time = \frac{WIP}{Throughput}$$

This formula indicates that WIP and cycle time are directly linked. Hopp & Spearman (2008) conclude that a short cycle time supports both lower costs and higher sales, which is beneficial for a high Return on investment (ROI). To reduce the cycle time and therefore also minimize the WIP one can reduce the utilization or diminish variability in arrivals and processing times, decreasing the likelihood of bottlenecks and delays (Hopp & Spearman, 2008).

### *Utilization*

Utilization refers to the extent to which a workstation or production resource is used compared to its full capacity. Reducing utilization, to decrease cycle time conflicts with another Lean principle of full utilization of resources, because low utilization causes the loss of effective capacity and therefore create waste.

Trade-offs have to be made for utilization and cycle time. Low utilization is required for fast response and short cycle times. Although a Lean principle aims for zero waste and 100% utilization, with a little bit of a variability (naturally unavoidable), a system with 100% utilization 'blows up', causing increasing cycle times. In a process with high variability, utilization should be low to make sure the system is not overloading. Understanding how variability degrades performance in the manufacturing process is essential for process improvements, because many problems are often indirectly related to variability (Hopp & Spearman, 2008).

### *Bottleneck*

Besides variability, identifying bottlenecks is crucial for process optimization. A bottleneck is a task in the production process where capacity is limited, causing delays and reducing overall output. To effectively reduce cycle time, utilization should be decreased at bottleneck stations, which dominate the manufacturing system's behaviour. Reducing variability at bottlenecks is also important to prevent negative impacts on the entire process (Hopp & Spearman, 2008). When different stations/machines have varying costs, the expensive steps should be the ones with the highest utilization. The cheaper stations can then provide excess capacity to compensate for variability in the high-cost steps (Wu et al., 2020).

### 2.2.4 KPIs

An objective function is needed, which should be minimized or maximized to determine how optimised a design, system or decision is. KPIs are metrics used to measure the objective function. The process of minimizing or maximizing the objective function is bounded to a set of restrictions, called constraints, such as capacity or lead times (Mahmoud, 2006).

Cooper (2002) reports that businesses most commonly use financial calculations for project selection and prioritisation. Methods are often employed to either rank projects against each other based on expected financial results, or to compare individual projects against a predefined hurdle rate to make go/no-go decisions. However, the study also reports that solely relying on financial tools does not lead to optimised business performances, and a more hybrid approach is advised for resource allocation and project selection (Cooper et al., 2002). This aligns with another study which concludes all KPIs can enable a high ROI, but multiple criteria should be included in the decision-making process (Puška et al., 2017). According to White (1996) popular strategies for optimisation indicators are cost, quality, time and production related. Bhatti et al. (2014) identify many indicators fitted to those strategies. In Table 2 we present some KPIs obtained from literature that could be applied to the manufacturing process of X.

Table 2: Manufacturing KPIs (Bhatti et al., 2014; Hopp & Spearman, 2008)

| **Cost-related KPIs:** | **Time-related KPIs:** | **Quality-focused KPIs:** | **Productivity KPIs:** |
|---|---|---|---|
| Labour cost per unit | Throughput time | First pass yield | Worker productivity |
| Energy cost per unit | Wait time | Defect density | Machine utilization rate |
| Production costs | Cycle time | Rework rate | Output per labour hour |
| Material cost per unit | Break even time | Right First Time | WIP |
| Manufacturing cost per unit | Bottleneck rate | Rate of Return | Overall equipment effectiveness |

Additionally, ROI is a widely used financial metric to calculate whether a business or investment is generating money. The ROI is calculated with the following formula (Hopp & Spearman, 2008):

$$ROI = \frac{profit}{assets}$$

$$(Profit = revenue - costs)$$

However, due to the inherent uncertainty of investments, it is very difficult to make an estimation of the expected investment costs. Another method is to calculate the cycle time, as reduction in cycle time is beneficial for a high ROI (Section 2.2.3). The complex formulas that address cycle time are provided in Appendix B, including variation and utilization.

To summarize Section 2.2, selecting automation opportunities involves measuring their impact on process optimization through a hybrid approach, covering cost, time, quality, productivity, and financial measures. This method enables VDL to effectively track the impact of their optimisation efforts and make data-driven decisions to continuously improve their processes. Additionally, to maximize the benefits of automation, it is crucial to focus on reducing cycle time and identifying bottlenecks and variability. Before implementing automation, VDL should identify and eliminate waste using Lean Six Sigma methodologies, as this often proves to be more efficient than investing in automation.

## 2.3 Suitability of automation investment opportunities

In this section, we focus on evaluating the suitability of automation opportunities, distinct from specific economic, ergonomic or quality considerations. We explore how to determine if automation is possible in the first place and how to select the most promising opportunities, addressing Sub question 1.3:

"How can the suitability of automation investment opportunities be objectively assed to facilitate decision-making?"

As discussed in Section 2.1.2 it is crucial to identify whether there is potential for automation. Therefore, Section 2.3.1 explores successful methods used at VDL, which are Level of Automation (LoA) and the DYNAMO method, by Frohm (2008). However, solely relying on these methods for automation decision making does not yield the desired solutions for VDL. As it is very time consuming and expensive to automate all opportunities, we explore selection methods in Section 2.3.2.

### 2.3.1 Level of Automation

A manufacturing process consists out of multiple sub processes containing various tasks. The LoA usually varies per task and these tasks cannot simply be assigned fully manual or fully automated, because there are many levels in between. Therefore, the degree of automation for each task is categorized using a LoA scale (Frohm, 2008).

Different theories exist on determining the LoA in a process. The DYNAMO method, specifically designed for manufacturing processes, divides the LoA into two categories: Mechanical & Equipment (M&E) and Information & Control (I&C), as shown in Table 3. This approach enables a thorough analysis of both the physical and cognitive aspects of processes. Cognitive aspects meaning the control and support of the physical aspects. Additionally, each task can be independently scaled from level 1 to 7 in each aspect (Frohm, 2008).

Table 3: Levels of Automation (Frohm, 2008)

| LoA | Mechanical & Equipment | Information & Control |
|---|---|---|
| 1 | **Totally manual** – Totally manual work, no tools are used, only the user own muscle power. E.g. The users own muscle power | **Totally manual** – The user creates his /her own understanding for the situation and develops his/her course of action based on his/her experience and knowledge. E.g. The users earlier experience and knowledge |
| 2 | **Static hand tool** – Manual work with support of static tool. E.g. Screwdriver | **Decision giving** – The user gets information on what to do, or proposal on how the task can be achieved. E.g. work order |
| 3 | **Flexible hand tool** – Manual work with support of flexible tool. E.g. Flexible spanner | **Teaching** - The user gets instruction on how the task can be achieved. E.g. Checklists, manuals |
| 4 | **Automated hand tool** – Manual work with support of automated tool. E.g. Hydraulic bolt driver | **Questioning** – The technology question the execution, if the execution deviate from what the technology consider being suitable. E.g. verification before action |
| 5 | **Static machine/workstation** – Automatic work by a machine that is designed for a specific task. E.g. Lathe | **Supervision** – The technology calls for the user's attention and directs it to the present task. E.g. Alarms |
| 6 | **Flexible machine/workstation** – Automatic work by a machine that can be reconfigured for different tasks. E.g. CNC-machine | **Intervene** – The technology takes over and corrects the action, if the executions deviate from what the technology consider being suitable. E.g. Thermostat |
| 7 | **Totally automatic** - Totally automatic work, the machine solve all deviations or problems that occur by itself. E.g. Autonomous systems | **Totally automatic** - Totally automatic work, the machine solve all deviations or problems that occur by itself. E.g. Autonomous systems |

To determine if there is room for automation the current and relevant maximum LoA should be identified. The relevant maximum is the highest LoA of possible beneficial technical solutions for a task. If there is a gap between the current LoA and the relevant maximum, it indicates an opportunity to increase the LoA. Additionally, the relevant minimum LoA, is the degree of automation needed to produce a product with sufficient quality according to the client. Ideally, the current LoA should fall somewhere between the relevant minimum and maximum. If the current LoA is below the relevant minimum, the company should automate, as the current level is insufficient to meet quality requirements (Frohm, 2008).

### 2.3.2 Project selection

Hamzeh & Xu (2019) observe strengths and weaknesses in technology selection methods. Hybrid methods represent the foremost best option when it comes to decision-making for investments. This method can consider both tangible and intangible factors under the uncertainty inherent in investment decisions (Hamzeh & Xu, 2019). For example, Ertugrul Karsak & Tolga (2001) combine fuzzy logic and modelling. Fuzzy logic incorporates uncertainty in the decision-making process, because there are unknown exact numerical values. It can deal with imprecise information and handle human judgment (Hamzeh & Xu, 2019). Figure 3 shows an example.

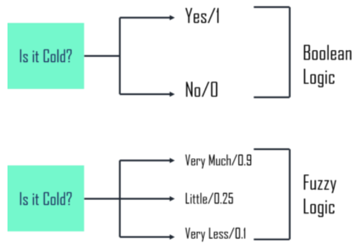



Figure 3: Fuzzy Logic in AI (Kappagantula, 2019)

Their hybrid approach comprehensively evaluates investment opportunities by considering both economic and strategic factors, allowing a more holistic assessment. More recently, Hajghasem et al. (2022) combine fuzzy logic with programming, by creating a mathematical model using fuzzy multi-objective programming selecting the optimal LoA. Additionally, Tiwari et al. (2013) integrate Six Sigma, fuzzy Analytic Hierarchy Process (AHP) and modelling to support project selection, as shown in Figure 4. AHP is a multi-criteria decision-making method that allows structuring complex problems hierarchically and making pairwise comparisons to determine the relative importance of alternatives and criteria (Pekin et al., 2006). To address the limitations of traditional AHP in handling ambiguity and uncertainty, researchers have integrated it with other methods, such as fuzzy logic, to enhance the robustness of the decision-making process (Hamzeh & Xu, 2019).

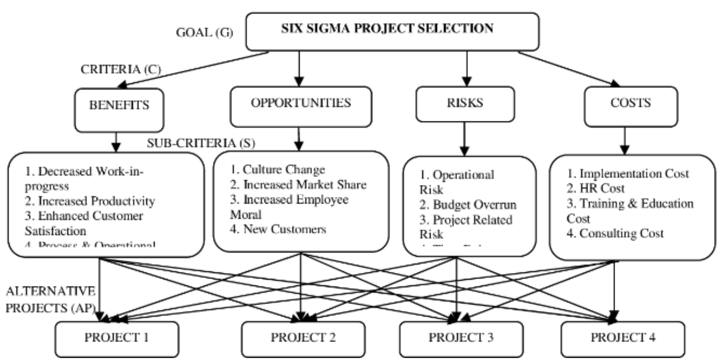



Figure 4: Project selection method by (Tiwari et al., 2013)

These studies demonstrate the value of hybrid methods that leverage a combination of quantitative and qualitative evaluation techniques, as well as the integration of various analytical perspectives.

## 2.4 Economic impact

With Sub question 1.4 we address the economic impact of automation opportunities:

“How can the expected economic impacts of potential investment opportunities be determined?”

Section 2.2.4 provides potential metrics for measuring the economic impact of automation investments and can be incorporated in project selection methods (Section 2.3.2). Additionally, principles from factory physics can be applied to rate economic yields through cycle time reduction and utilization. In this section, we further explore how to assess the economic impact, by assigning the appropriate LoA for each task, based on process variability.

### 2.4.1 The appropriate LoA

As discussed in Section 2.2.4, financial calculations are effective metrics for investment decisions. However, the low availability of data complicates the use of the formulas provided in Appendix B. Angel (2016) introduces a variability taxonomy that informs the maximum viable LoA for tasks in a manufacturing process. The framework describes process variability in tasks and assumes automation levels are inversely proportional to process variability. High process variability and low understanding of the variabilities results in a lower LoA advice, because these tasks require more human involvement, as discussed in Section 2.2.3. Additionally, high process variability usually requires more advanced automation with greater intelligence, which comes at a significantly higher cost (Angel, 2016).

Angel (2016) applies the framework to established processes with consistent quality and safety standards, validating it in high-end, low-volume, manual manufacturing environments that require high precision and regulation.

### 2.4.2 Process variability identification

Angel (2016) identifies five crucial attributes that describe an important characteristic or aspect of the manufacturing process when calculating process variability: outputs, inputs, strategy, time, and requirements. The process variability can be calculated with parameters that describe the process variability for each attribute. These parameters may vary as not every manufacturing process encompasses every variability. Experts evaluate the importance of parameters using the AHP method, which is described in Section 2.3.2 as a project prioritization method, but can also serve as a parameter prioritization method. Table 4 shows the attributes and parameters that describe process variability according to Angel's framework (2016). We simplify and detail these parameters in Section 4.1.

Table 4: Process variability attributes and parameters (Angel, 2016)

| Attribute | Parameter |
|---|---|
| Output | Quantity → # sources of variability in outputs |
| | Diversification → # different outputs affected by variability |
| | Interval of variability → Determines whether the range of variability is delimited or not |
| | Interdependency → Acting on one source of variability doesn't affect other sources of variability |
| Inputs (parts, tools, stimuli, data, information cues, procedure) | Quantity → # sources of variability in inputs |
| | Diversification → # different outputs affected by variability |
| | Interval of variability → Determines whether the range of variability is delimited or not |
| | Interdependency → Acting on one source of variability doesn't affect other sources of variability |
| Strategy | Number of alternatives → # different ways to solve variability |
| | Number of actions → # different actions required to overcome the problem |
| | Pattern → Actions which follow a repeated pattern |
| Time | Concurrency → Sources of variability are presented in sequence or concurrently |
| | Time availability → Time available is enough to eliminate variability |
| Requirements | Sensorial → Domain of the sensorial features needed to cope with variability (visual, hearing, tactile…) |
| | Cognitive requisite → To solve the variation |
| | Physical requisite → To solve the variation (space, force, torque, etc...) |

Angel (2016) utilizes three methods for obtaining the process information to assign the parameter values: company documentation, direct observation during manufacturing processes, and interviews with operators carrying out tasks. Company documentation serves as a primary source of information regarding variabilities in machines, parts, and processes. Observation is particularly valuable for exploring the manufacturing environment and identifying variabilities. Interviews play a crucial role in clarifying and validating the data collected, while open-ended questions provide qualitative insights into additional variabilities within the manufacturing process (Goh et al., 2020).

To summarize, Chapter 2 examines various methodologies for evaluating automation investment opportunities to optimize the manufacturing process of product X. Numerous optimisation methods are available and factory physics helps to clarify the underlying theories of these methods. We prefer a hybrid approach for selection of automation opportunities and outline different formulas and KPIs to evaluate these opportunities. However, missing data and the inherent uncertainty in automation investments can complicate their application. One promising approach for evaluating automation investments is the calculation of cycle time reduction, as factory physics suggests that effective reductions can be achieved by focusing on tasks with high utilization. Furthermore, the variability framework offers opportunity for assessing the economic feasibility of automation in high-tech, manual manufacturing processes, where high process variability is associated with a low LoA recommendation. If we compare the current and maximum LoA (Section 2.3.1) with the appropriate LoA obtained through the variability framework, we can give a LoA advice.

# 3 Current situation

By answering Research question 2, this chapter addresses the exploration phase identified in Section 2.1.2:

> “What is the current situation at VDL?”

In Section 3.1 we obtain the goals and objectives of VDL, considering their strategy, current project management and automation benefits. We create a clear view of the manufacturing process and its specific tasks in Section 3.2 and in Section 3.3, we analyse the manufacturing process on automation opportunities.

## 3.1 Goals and objectives

To ensure that the decision-making strategy aligns with the corporate goals, it is crucial to identify the company's core values, integrating them in the objectives. We answer Sub question 2.1:

> “What are the goals and objectives of VDL’s manufacturing and assembly operations?”

In Section 3.1.1 we explore the general strategy at VDL ETG. In Section 3.1.2 we describe how VDL currently addresses their goals and in Section 3.1.3 we integrate the identified objectives into the automation strategy.

### 3.1.1 Company Strategy

The strategy of VDL ETG is based on four pillars: Quality, Lead time, Technique and Costs (QLTC).

> “**Q**uality: aim for “zero defects” quality levels for regular production.
>
> First time right in development and First Article Production
>
> **L**ead time: Offering the highest standards in delivery time and reliability
>
> **T**echnique: Offering the highest standards in technological level
>
> **C**osts: Offering the highest standards in product costs”

The QLTC strategy also applies on the manufacturing process of product X. VDL ETG incorporates Lean Six Sigma (Section 2.2.2) for reaching the goals of QLTC. In addition, VDL ETG also incorporates the Business Excellence philosophy in management (VDL, 2023a). This philosophy is focused on continuous performance improvement and exceeding stakeholder expectations. Initially known as Quality Management, it has evolved and is now commonly referred to as Business Excellence, emphasizing the importance of all aspects of a business such as processes, products, services, and culture within an organization (Mann et al., 2012).

Improvement projects at VDL are guided by a roadmap (VDL, 2023a) that defines four stages used during the crucial product lifecycle period of peak sales and profits. Developed by VDL, this roadmap is based on the stages and methodologies of Liker (2004) and Theisens (2018), integrating theoretical optimization principles with practical adaptation to address VDL's specific environment and operational needs.

1. Basics: before organizations can make any process improvement with Lean and Six Sigma (Section 2.2.2), it is required that a solid foundation is put in place. This includes securing commitment from decision-makers (Section 2.1.2) and setting clear goals and objectives (Section 2.1.1).
2. Lean Manufacturing: Establish a culture of CIP, reduce waste, and standardize flows.
3. Six Sigma: Goes beyond waste reduction by using data-driven tools and statistical analysis to identify, measure, and reduce process variation.
4. Reliability: Optimise product and process development and design for the full lifecycle.(Liker, 2004; Theisens et al., 2018)

Product X is currently in this crucial period and in the second stage of the roadmap. VDL incorporates an Operational Excellence department dedicated to improvement within the company, however many improvement concepts remain in the early stages of implementation. In practice, there is a lack of comprehensive data on the application of these concepts for product X. Over the past years, VDL ETG Almelo has experienced significant growth. Production increase was prioritized, causing a lack of focus on the implementation of optimisation strategies.

### 3.1.2 Current drivers for automation

To identify important factors in the decision-making for investments, we analyse the current process improvement management at the T&D department through meetings with managers and engineers. The T&D department has a supporting role to the factory, providing concepts and tools that assist the factory operations. The main driver for new technologies from the T&D department is currently quality improvements. Economic considerations and ergonomic problems also influence decision-making on new technology investments. Currently, economic factors are estimated based on the opinions and past experiences of decision-makers and engineers, rather than on a rigorous, data-driven assessment, which is preferred but not yet available.

The T&D department is eager to develop innovative technologies and optimise the production process, besides solving quality issues. They want to leverage the investment decisions of the managers, by gaining knowledge on the need of the factory. The decision-makers recognize the potential of new automation technologies, but struggle to fully understand and act on this potential.

### 3.1.3 Automation objectives product X

Popular benefits of automation are cost savings, enhanced competitive position and increased efficiency and productivity (Frohm et al., 2006). Through meetings and conversations with operators, managers, and engineers we validate the relevance of the advantages and disadvantages identified by Frohm et al. (2016) for the manufacturing process of product X. We present the relevant advantages and disadvantages in Table 5.

Table 5: advantages and disadvantages of automating manufacturing processes at VDL

| Advantages | Disadvantages |
|---|---|
| Cost savings | Potential for production disturbances |
| Decreased need for employees | Increased complexity of production systems |
| Increased efficiency and productivity | Challenges with product variants |
| Strengthened competitive position | Higher maintenance costs |
| Improved quality | Need for product adaptations for automated production |
| Improved working environment:<br>➢ Elimination of monotonous, physically demanding, and unsafe tasks for workers | High investment costs:<br>➢ Time<br>➢ Money<br>➢ Training of employees |

Addressing Sub question 2.1, we conclude that the economic impact of automation opportunities is crucial in the decision-making. Each factor in Table 5 can either positively or negatively impact financial performance. Benefits such as reduction in labour hours, increased efficiency and productivity, improved quality, greater consistency, and enhanced material efficiency directly influence the bottom line by lowering expenses and increasing output. Improved flexibility causes a strengthened competitive position and increases market share and revenue. An improved working environment can decrease employee turnover and associated costs.

Non-economic advantages are also crucial in automation decision-making. For instance, when quality issues arise during the manufacturing process, VDL may decide to develop new tools, regardless of the complexity or cost, to ensure products meet client requirements. However quality issues are currently mainly influenced by the supply of insufficient-quality materials. While humans can identify these issues with experience, tooling requires specific programming to address them.

Another significant non-economic advantage of automation is an improved working environment. VDL adheres to strict guidelines aimed at ensuring a safe and comfortable working environment for employees, prioritizing their well-being and physical comfort. Currently, no ergonomic issues exist according to company data. VDL's analysis of working posture, toxic materials, and other factors scores sufficiently. Besides, no employees have fallen ill or had to leave their jobs due to health issues related to the manufacturing process of product X.

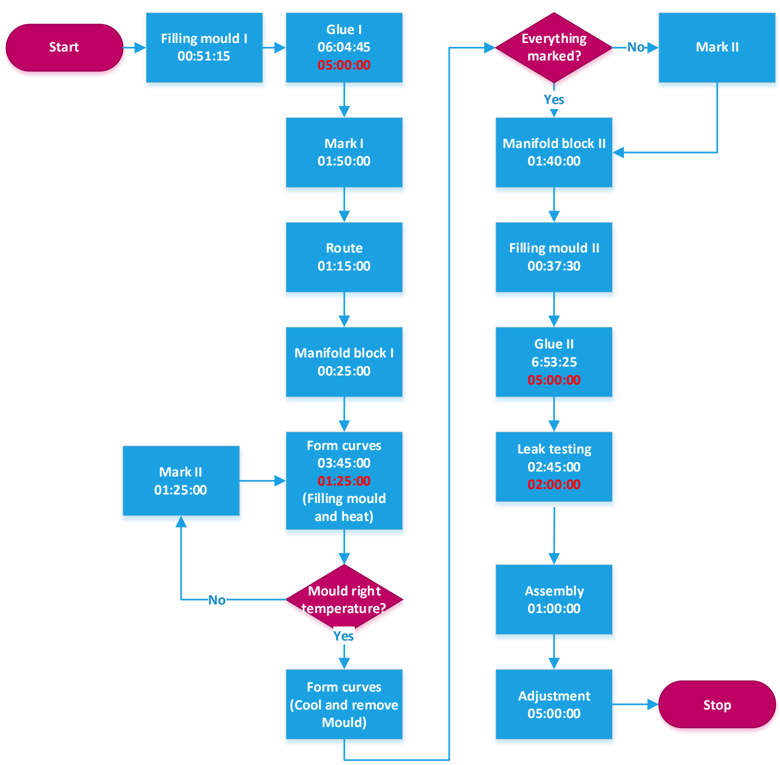
During the early stages of tool development, VDL finds it challenging to express all benefits financially. Therefore we assess the economic and non-economic impacts separately in Chapter 5.

## 3.2 Current manufacturing process of product X

To identify potential automation opportunities, it is crucial to have a thorough understanding of the manufacturing process of product X. A flow chart depicted in Figure 5 shows the sequential steps product X follows in the current manufacturing process (VDL, 2023b). Each block in the flowchart represents a task, which contains many sub tasks. Although the company has flow charts per task within the process, they are not included in this report.

Additionally, Figure 5 provides an overview of the average cycle time of each task, including waiting time. Times are scaled by a factor (Appendix G), to maintain data confidentiality. VDL obtained these times by observing and clocking the execution of the tasks in the production process. The cycle time is the effective production time, excluding process times that are not directly involved in production, such as operator breaks or waiting for materials. The waiting times in Figure 5 account for about a quarter of the total production time. These delays, such as glue drying are difficult to reduce through automation. As depicted in Figure 5, the task ‘Form curves’ is the only task where operators simultaneously work on the same product with the next task during the waiting time.

Through observations in the production process we identify these tasks and verify the flow chart. While measurements of the production steps are accurate, it is important to acknowledge that these cycle times can fluctuate based on factors such as employee experience and working speed.




[1]Figure 5: A flowchart with scaled cycle times and waiting times of product X (VDL, 2023b)

[1] Waiting times are depicted in red, with all numbers scaled for confidentiality.

In general, the cycle times in Figure 5 do not account for variability. VDL's post-calculation, which does include variability shows significant differences in average labour hours per product. This variation is caused by multiple factors such as employees assisting colleagues during their tasks, being called away to address issues in other processes and misreported labour hours. The post-calculation numbers reflect the total cycle time for the entire production cycle of a product and do not provide detailed insights into specific tasks. Misreporting of labour hours makes the numbers insufficient to draw definitive conclusions. However, with more accurate post-calculation measurements, we can assess variability in cycle times using formulas outlined in Appendix B, addressing factory physics (Section 2.2.3).

In Section 3.1.3, we highlight the importance of considering the economic impact in automation decision-making. Cost calculations can be made using the cycle times and hourly cost rates assigned to each production step. Currently, there is no variation in hourly cost rate per task. The hourly cost rate accounts for both variable and fixed costs. However, the constant costs are minimal in comparison to the variable costs, making the variable costs the primary driver of the overall costs.

## 3.3 Automation potential

The highly manual manufacturing process of product X offers opportunities for new tools. In this section we explore automation opportunities, addressing Sub question 2.3:

> “Which tasks can be automated in the manufacturing process of product X?”

VDL employs the DYNAMO method (Section 2.3.1) and decision trees by Halbesma (2024) to streamline assigning the LoA. With this structured approach Halbesma (2024) estimates and validates the current, minimum, and maximum LoA for all tasks in the manufacturing process of product X.

The manufacturing process of product X includes 92 sub tasks. Table 6 provides a sample of the estimated current, minimum and maximal LoA for the subtasks within the task ‘Assembly’ (Section 3.2). The color-coded results highlight automation opportunities in green. The difference between the estimated minimum and current LoA is sometimes negative, which indicates that the current LoA falls below the minimum required LoA to produce products of sufficient required quality and therefore must be increased.

The task ‘Assembly’ presents the most promising automation opportunities considering all results in the manufacturing process of product X, because its sub tasks show the highest maximum difference. When the assigned LoA shows little or no potential for further automation, the subtask either already has a high LoA or can only be applied to one of the two categories: M&E or I&C (Section 2.3.1), resulting in an automatic score of 0 for the other category. For example, setting an alarm clock involves only the cognitive aspect, and therefore falls exclusively under I&C.

Table 6 : Assessment of automation opportunities (Halbesma, 2024)

| | Mechanical and equipment | | | | | Information and control | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| Task description | Current | Min | Min difference | Max | Max difference | Current | Min | Min difference | Max | Max difference |
| **Assembly** | | 3 | | 2 | | | 3 | | 3 | |
| Check for dirt | 0 | 0 | 0 | 0 | 0 | 3 | 3 | 0 | 3 | 0 |
| Orient product correctly | 1 | 1 | 0 | 6 | 5 | 3 | 3 | 0 | 6 | 3 |
| Place a mat | 1 | 1 | 0 | 6 | 5 | 3 | 3 | 0 | 6 | 3 |
| Make a decision | 2 | 2 | 0 | 6 | 4 | 3 | 3 | 0 | 6 | 3 |
| Tighten and loosen screws | 3 | 3 | 0 | 6 | 3 | 3 | 3 | 0 | 6 | 3 |
| Apply Fomblin | 2 | 2 | 0 | 6 | 4 | 3 | 3 | 0 | 6 | 3 |
| Place stickers | 1 | 1 | 0 | 6 | 5 | 3 | 3 | 0 | 6 | 3 |
| Install tie wraps | 1 | 1 | 0 | 6 | 5 | 3 | 3 | 0 | 6 | 3 |
| Cut ties | 2 | 2 | 0 | 6 | 4 | 3 | 3 | 0 | 6 | 3 |
| Install earth cable | 2 | 2 | 0 | 6 | 4 | 3 | 3 | 0 | 6 | 3 |
| Placing strain reliefs | 2 | 2 | 0 | 3 | 1 | 3 | 3 | 0 | 3 | 0 |
| Attach strain relief to CSI hood | 2 | 2 | 0 | 4 | 2 | 3 | 3 | 0 | 4 | 1 |
| Place hoses in trench | 1 | 1 | 0 | 3 | 2 | 3 | 3 | 0 | 4 | 1 |
| Mount manifold on CSI | 2 | 2 | 0 | 4 | 2 | 3 | 3 | 0 | 5 | 2 |
| Route product | 1 | 1 | 0 | 2 | 1 | 3 | 3 | 0 | 4 | 1 |
| Place top and cover plate | 2 | 2 | 0 | 6 | 4 | 3 | 3 | 0 | 4 | 1 |
| Installing product assemblies | 2 | 2 | 0 | 6 | 4 | 3 | 3 | 0 | 4 | 1 |

Addressing Sub question 2.3, we conclude that with the assessment of automation opportunities in the manufacturing process of product X, all tasks exhibit potential for automation in at least one of the two categories.

In conclusion, in Chapter 3 we explore the current situation at VDL. We currently do not identify automation benefits for ergonomic and quality issues in the manufacturing process of product X. Therefore, we prioritise cost reduction and investment benefits in the decision-making process. We should focus on economic decision-making factors that with a method can be estimated relatively quick. Cost reduction is linked to cycle time reduction, achieved by decreasing labour hours. Investment benefits can be objectively assessed through process variability, focussing on complexity and challenges with irregularities.

# 4 Variability framework design

In Section 2.4.1 we introduce a variability framework that determines the appropriate LoA, considering the economic impact of automation investments. This chapter develops and simplifies a variability framework specifically applicable to the manufacturing process of product X. The framework is one of the indicators for determining the economic impact in Section 5.2 and indicates the economic viability of automation investments in the final tool. In Section 4.1 we establish a clear and common understanding of the parameters and in Section 4.2 we examine the framework's weights. In Section 4.3 we finalize the framework. Finally, we apply and test the framework on two specific tasks: Fill Mould I (Section 4.4) and Assembly (Section 4.5).

## 4.1 Interpretation of parameters

In literature, two reports on a process variability taxonomy for determining the optimal LoA have been identified, which share Angel as a common author. The reports overlap, but parameters and their states are sometimes interpreted differently (Angel, 2016; Goh et al., 2020). Utilizing these reports, we describe our own simplified understanding of the parameters and their states that describe the process variability in the five attributes (Output, Input, Strategy, Time and Requirements).

**Output** is all goods that are transformed during the task of the manufacturing process of a product, including flawed products.

- **Number of variability sources** considers the number of different variability characteristics identified in the outputs. The different kinds of deviations within a product, for example the produced products have different weights, dimensions or surface roughness. If there is no variability identified in the output, the parameter state is 'not applicable' and this applies to the other parameters as well.
- **Diversification** is the number of different outputs affected by the identified variability characteristic. In the manufacturing process of product X, typically one product is produced with slight variations, resulting in a maximum of two different outputs. However, certain specific tasks may yield more varied outputs affected by variability.
- **Interval of variability** considers whether the variability boundaries are known (e.g., a maximum weight of 70 kg) or unknown (e.g., it cannot be too heavy). If the interval of variability is 'unknown', it causes increasing uncertainty and thus process variability. Before implementing automation, the interval of variability needs to be 'known' and therefore measured if unknown.
- **Interdependency** considers if the identified variabilities depend on each other. If we act on one source of variability, does it also change another source of variability? For example, changing surface roughness might also change the dimensions. If at least one source of variability is independent (minimum of two sources required), the state is 'independent'.

**Input** considers the same parameters as output, however at this attribute they describe the variability in the inputs. Inputs can be everything that is needed to perform a task, for example tools, raw materials, guidelines and data (Angel, 2016).

- **Number of variability sources** identifies the number of variability in the inputs. For example, number of dirt particles on materials and sharpness of tools.
- **Diversification** considers the number of inputs affected by the variability source. For example, are the dirt particles only on the material or also on the tool?
- **Interval of variability**: are the boundaries of variability known or unknown? For example, is it clear how sharp a tool needs to be or is it based on human judgment?
- **Interdependency**: can we change one source of variability and simultaneously positively or negatively impact another source of variability?

**Strategy** is defined as a form of control that determines the task procedure. It captures the variability in the operators approach to complete the task and can be defined by three variability parameters (Goh et al., 2020).

- **Number of alternatives** refers to the variety of pathways available to complete the task. If there are two operators they usually can have different proceedings. A high number of alternatives increases process variability. A robot necessitates a predefined path, it cannot decide how to manage variability. Therefore, if the task consists of multiple alternatives it should be standardized first, before automating.
- **Number of actions**. When performing a task, we often manage a 'source of variability', as described for the attributes input and output. The parameter 'number of actions' is the number of necessary actions to successfully cope with this variability. Every verb is counted as an action and repetition of actions should not be counted. For example, surface roughness can be managed with a tool, where the operators needs to:
  1) Check the tool condition 2) recondition the tool and 3) shape the tool.

  Angel (2016) reports the difficulty in making a distinction between actions that are executed to transform inputs into outputs and actions to handle variability. However, all actions need to be considered for automation, which is why we also need to identify the actions that handle the variability. Angel (2016) reports a sufficiently robust defined parameter when an in depth process analysis is conducted and clear instructions are provided for defining the parameter.

- **Patterned actions**: some actions are repeated and follow a pattern, reducing process variability. This is concluded when a minimal of three identified actions are repeatedly executed in the same pattern.

**Time** is just like the attribute strategy concerned about the way a task is performed (Angel, 2016).

- **Concurrency** considers if sources of variability are introduced and handled at the same time or in a sequence. Multi-tasking increases the chance of process variability. If at least two sources of variability (parameter input and output) are managed in the same action, the state of the parameter is concurrent. For example, dependent on the sharpness of the tool, digging force and digging time are managed simultaneously, resulting in the state ‘concurrent’.

- **Time availability** assesses whether operators are constrained by time pressure. When operators are under time pressure, variability tends to emerge more quickly.

**Requirements** are the mechanisms that enable the task to be performed (Goh et al., 2020).

- **Sensorial prerequisite** addresses the number of sensorial features needed to overcome variability. For example, vision or the auditory sense could be needed to detect variability.
- **Cognitive prerequisite** is any mental process, such as judgment, that addresses variability.
- **Physical prerequisite** evaluates whether every individual can perform the task. If the task involves heavy lifting or requires precision, a physical prerequisite exists. This parameter addresses the fact that physically demanding tasks can cause operators to lose focus more quickly, leading to increased variability.

## 4.2 Weight validation

In Angel's (2016) framework, weights assigned to parameters are averaged from three aeronautical experts, each with over five years of experience in manufacturing processes. Despite differences between the aeronautical and semiconductor industry, the characteristics of the aeronautical industry (Section 2.4.1) closely resemble those of the semiconductor industry, suggesting that these weights could be relevant for the manufacturing process of product X.

To verify this, an engineer at VDL, experienced in the semiconductor industry, assigns weights to parameters using the AHP method. This method compares parameters one-to-one on importance as discussed in Section 2.3.2. An AHP excel template developed by Barnard (2016) is utilized and validated first. For each of the three experts in Angel’s (2016) report, we individually enter their assigned importance for the parameters into the template (Barnard, 2016). Upon doing so, we verify that the tool generates the same set of weights as reported by Angel (2016).

Surprisingly, we also find that all three experts from Angel (2016) do not pass the consistency check of the AHP tool, indicating that their comparisons are not acceptable. The inconsistencies in assigning the importance of parameters are 12%, 13%, and 22%, while the maximum allowable inconsistency is 10% (Barnard, 2016). Angel (2016) does not mention a consistency check or any inconsistency in the assigned weights. However, Angel (2016) successfully applies the proposed variability taxonomy, validating the framework, which suggests that the weights are still applicable.

The VDL engineer also does not pass the consistency check. This failure is likely due to a lack of knowledge and understanding about process variability and its parameters. In contrast, a second VDL engineer, with more experience in process optimization, successfully assigns weights and passes the consistency check. Appendix C includes the assigned priorities entered into the template for Expert 1 from Angel’s (2016) report, as well as for the two VDL experts.

The resulting weights of the second engineer at VDL highly differ from the weights from Angel (2016). However, the three experts in the literature also show substantial variation in their resulting weights, possibly due to different parameter interpretations and the lack of concrete guidance. To resolve these discrepancies, we advise fostering a discussion with the experts to understand their reasoning behind prioritising certain parameters, possibly leading to consensus. However, contacting the literature experts for further discussion is currently not possible.

Due to time constraints, no more engineers at VDL are asked to assign weights. In the future, the company can fine-tune the weights according to their specific needs and develop their own interpretations of the parameters. They can involve various engineers in assigning weights to the parameters, compare the results, and foster discussions to reach a consensus. As the weights of Angel's (2016) framework show appropriate outcomes in a similar manufacturing process we continue with those weights in this research.

## 4.3 Framework development

Based on Angel's (2016) framework we develop a process variability framework to apply on tasks in the manufacturing process of product X. We first elaborate on the left side of the framework as depicted in Figure 6. The first column presents the attributes, which are the characteristics of the process we need to take into account when calculating process variability (Section 2.4.2). In the second column we list the parameters that describe the process variability in the attributes. The framework incorporates fuzzy logic (Section 2.3.2), by including dropdown menus with different possible states of the parameters in the third column. Figure 6 shows an example of a dropdown menu for the parameter 'Interval of variability'. This approach enhances the ease of use and robustness in outcomes. Once values are entered, experts can leave comments in the fourth column to note detailed comments about assigned values or any specific considerations.

| Attribute | Parameter | Result | Comment |
|---|---|---|---|
| **Outputs** | Number of variability sources | | |
| | Interval of variability | Not applicable<br>Fixed boundaries<br>Unknown | |
| | Diversification | | |
| | Interdependency | | |
| **Inputs** | Number of variability sources | | |
| | Interval of variability | | |
| | Diversification | | |
| | Interdependency | | |
| **Strategy** | Number of alternatives | | |
| | Number of actions | | |
| | Patterned actions | | |
| **Time** | Concurrency | | |
| | Time availability | | |
| **Requirements** | Sensorial | | |
| | Cognitive requisite | | |
| | Physical prerequisite | | |

Figure 6: Left side of the framework

In the fifth and sixth column we include help questions and short explanations of the parameters to guide experts in assessing values to parameters. Clicking on these cells reveals examples, as depicted in Figure 7.

| Parameter | Help question | Explanation (Click on explanation for eleboration) |
| --- | --- | --- |
| Number of variability sources | What kind of differences do you notice differences between outputs? | # sources of variability in outputs |
| Interval of variability | Is it clear how big the difference may be or is there a max/min? | Determines whether the range of variability is marked or not |
| Diversification | What is the amount of different kind of outputs affected by the variability? | # different outputs affected by variability |
| Interdependency | If we act on one source of variability does it also affact another source? | Acting on one source of variability doesn't affect other sources of variability |
| Number of variability sources | What kind of differences do you notice differences between inputs? | # sources of variability in inputs |
| Interval of variability | Are the boundaries of variability fixed or not? | Determines whether the range of variability is known or not |
| Diversification | What input is affected by the variability? (tool, material, data) | # different inputs affected by variability |
| Interdependency | If you act on one source of variability does it affect other sources? | Acting on one source of variability doesn't affect other sources of variability |
| Number of alternatives | How many different paths are there to complete a task? | # different ways to solve variability |
| Number of actions | What is the number of different actions required to solve variability? (every verb is an ac | # different actions required to overcome the problem |
| Patterned actions | Are there a minimal of three identified actions repeatedly executed in the same pattern? | Actions which follow a repeated pattern |
| Concurrency | Is the operator multi tasking or are the sources of variability handled in a sequence? | Sources of variability are presented in sequence or concurrently |
| Time availability | Is there a time pressure? | Time available is enough to eliminate [illegible] |
| Sensorial | Which of the five senses does the operator use? | Domain of the sensorial features nee [illegible] isual, he |
| Cognitive requisite | Is there a mental process that addresses variability, for example judgement? | To solve the variation [illegible] |
| Physical prerequisite | Is the task physically demanding? | To solve the variation (space, force, t [illegible] |

Concurrent describes when, at least two sources of variability, have to be managed in the same action, ex. when selection of the tool is

Figure 7: Middle part process variability framework

In the right side of the framework, we perform calculations using weights assigned by experts (Section 4.2) depicted in Figure 8 in the column called 'Weights'. Appendix D includes a table with parameter states and their corresponding parameter values, which range from 0 to 10 (0- no variability, 10- high variability). We multiply the resulting parameter values, by their corresponding weight. The weighted sum represents the variability score. A low score indicates suitability for high automation, while a high score indicates low automation is appropriate.

The table in the bottom of Figure 8 indicates the LoA for each category. We do not distinguish between the physical and cognitive category as Frohm (2008) does, as both are present at task level. We identify four categories: Low, Moderate, Considerable and High. LoA 1 and 2 are excluded, because they represent no or neglected automation. LoA 3 and 4 are grouped as 'Low', because they both indicate manual tasks with handheld tools.

The table in the bottom also includes the upper boundaries for each category, indicating which category corresponds to the resulting total weighted value. Although the intervals differ from those in Angel's (2016) framework, the same method is used to obtain the upper boundaries: summing the maximum total weighted value and dividing it by 4, corresponding to the number of LoA categories. This discrepancy is currently inexplicable.

| Attribute | Parameter | Result | Weights | Values of results | Weigthed values | Advised LoA |
|---|---|---|---|---|---|---|
| **Outputs** | Number of variability sources | 2 | 3,00 | 2 | 0,06 | |
| | Interval of variability | Unknown | 11,20 | 10 | 1,12 | |
| | Diversification | 3 | 3,10 | 3 | 0,093 | |
| | Interdependency | Independent | 1,80 | 10 | 0,18 | |
| **Inputs** | Number of variability sources | 3 | 3,00 | 3 | 0,09 | |
| | Interval of variability | Unknown | 11,20 | 10 | 1,12 | |
| | Diversification | 2 | 3,10 | 2 | 0,062 | |
| | Interdependency | Dependent | 1,80 | 5 | 0,09 | |
| **Strategy** | Number of alternatives | 2 | 2,10 | 2 | 0,042 | |
| | Number of actions | 1 to 5 (low) | 1,50 | 0 | 0 | |
| | Patterned actions | Some actions patterned | 2,00 | 0 | 0 | |
| **Time** | Concurrency | Concurrent | 6,40 | 5 | 0,32 | |
| | Time availability | Sufficient | 21,00 | 0 | 0 | |
| **Requirements** | Sensorial | 3 | 4,70 | 3 | 0,141 | |
| | Cognitive requisite | Yes | 14,00 | 10 | 1,4 | |
| | Physical prerequisite | No | 10,10 | 0 | 0 | |
| | | | 100,00 | 65 | 4,718 | |
| | | | | | **Considerable** | **6** |
| **Levels of automation** | **Level** | **Upper boundries** | | | Filling mould I | |
| Low | 3 & 4 | 9,7 | | | | |
| Moderate | 5 | 7,275 | | | | |
| Considerable | 6 | 4,85 | | | | |
| High | 7 | 2,425 | | | | |

Figure 8: Right side of the framework

## 4.4 Fill mould I analysis

### *Expectations*

To validate and test the framework in practice, we initially apply it to the Fill Mould I task. Experts at VDL, estimate this task relatively easy to automate, based on their experience and expertise in automating high-tech manufacturing processes. By applying the framework to this task, we can assess whether it meets our expectations.

Through Quality reports, which include production guidelines and observations we identify relevant sources of variability. The most recent report on the Fill Mould I task, published in 2015 (VDL, 2015), is outdated, leading to missing or irrelevant identified variabilities. To ensure the accuracy and relevance of our data, we interview operators to validate our observations and identify any new variables (Appendix E.1). For example, material length was initially identified as a variability in the quality report (VDL, 2015), but through interviews we find that it is no longer relevant. Appendix E.2 presents a more detailed description on how the parameters values are finalized. Including identified variabilities through observations, quality reports and operator feedback.

### *Findings*

Figure 9 shows the identified variabilities and presents the calculated outputs in the framework. The two parameters, 'Interval of variability' and 'Cognitive requisite,' contribute the largest fraction to the total weighted value, restricting the advised LoA to be ‘High’. The interval of variability is often unknown, because the greatest variability source for the Fill mould I task is the irregularity in the quality of material supply, which can vary widely and change over time. Additionally, the parameter ‘Cognitive requisite’ significantly contributes to the total weighted value, as human judgement to recognize and handle these irregularities in supply is highly subjective, causing great process variability. Additionally, tools need to be specifically programmed to identify irregularities, whereas humans rely on experience. Other parameters are assigned low values as they do not significantly contribute to process variability in this task.

The total weighted value represents the process variability score, which is 4.718. Consequently, the recommended LoA is 6, classified as "considerable" (Section 4.3). This value corresponds with the expectations from experts at VDL.

| Attribute | Parameter | Result | Comment | Weights | Values of results | Weigthed values | Advised LoA |
|---|---|---|---|---|---|---|---|
| **Outputs** | Number of variability sources | 2 | Sequence, material, allignment | 3,00 | 2 | 0,06 | |
| | Interval of variability | Unknown | Unknown material sufficiency | 11,20 | 10 | 1,12 | |
| | Diversification | 3 | Three slightly different outputs | 3,10 | 3 | 0,093 | |
| | Interdependency | Independent | Sequence is independent of the others | 1,80 | 10 | 0,18 | |
| **Inputs** | Number of variability sources | 3 | Material thickness, contamination, twisting | 3,00 | 3 | 0,09 | |
| | Interval of variability | Unknown | | 11,20 | 10 | 1,12 | |
| | Diversification | 2 | Tool and product | 3,10 | 2 | 0,062 | |
| | Interdependency | Dependent | With controlling all sources are addressed | 1,80 | 5 | 0,09 | |
| **Strategy** | Number of alternatives | 2 | Two slightly different ways in mould position | 2,10 | 2 | 0,042 | |
| | Number of actions | 1 to 5 (low) | Check material, throw away and get new | 1,50 | 0 | 0 | |
| | Patterned actions | Some actions patterned | Get material, check, fill, check, close, again | 2,00 | 0 | 0 | |
| **Time** | Concurrency | Concurrent | Yes | 6,40 | 5 | 0,32 | |
| | Time availability | Sufficient | Always | 21,00 | 0 | 0 | |
| **Requirements** | Sensorial | 3 | Eyes, tactile and hearing | 4,70 | 3 | 0,141 | |
| | Cognitive requisite | Yes | | 14,00 | 10 | 1,4 | |
| | Physical prerequisite | No | | 10,10 | 0 | 0 | |
| | | | | 100,00 | 65 | 4,718 | |
| | | | | | | **Considerable** | 6 |

Figure 9: In- and output in framework Filling mould I

## 4.5 Assembly analysis

### *Expectations*

The 'Assembly' task in the manufacturing process of product X has the most subtasks and shows the greatest potential for automation (Section 3.3). However, experts at VDL expect high complexity, leading to a low LoA advice. Again, we use observations and quality reports to identify variabilities. Validation from an interview with a floor manager, who also serves as an operator, ensures data accuracy and identifies new variables (Appendix F.1). The Assembly task's most recent quality report (VDL, 2024), revised in 2024, demonstrates greater alignment with observations and data gathered through interviews than the outdated report of the Fill mould I task. This underscores the importance of up-to-date quality reports. Detailed outcomes are provided in Appendix F.2.

### *Findings*

Figure 10 shows that the process variability framework suggests a moderate advice, contradicting the expected low LoA. In general, we advise VDL to reconsider its expected LoA, based on the insights from interviews, observations and the framework's output, when there are discrepancies. However, the expected low advice seems accurate, as interviews indicate that humans in the assembly task compensate for a significant amount of variability. Frequent discrepancies in supply and guidelines require adjustments that machines may struggle to handle effectively. Therefore the discrepancy between the expected LoA advice and framework output arises, as the framework cannot adequately address challenges posed by human variability in the assembly process. Increasing the weight of the parameter 'number of variability sources' is recommended, increasing the realistic impact of the number of variability sources on process variability in the manufacturing process of product X.

Additionally, the discrepancy may be due to the high influence of the 'Time availability' parameter, which is not relevant to the manufacturing process of product X. Since VDL managers shield operators from time pressure, this parameter does not create variability in the manufacturing process. However, the 'Time availability' parameter does have the highest weight of all parameters, restricting the total weighted value from reaching a higher, more relevant value, that aligns with the expected LoA. For example, if we assign the state of the 'Time availability' parameter as 'insufficient', the total weighted value significantly increases and the framework provides the expected low LoA. Therefore, we recommend excluding this parameter from the framework.

| Parameter | Result | Comments | Weights | Values of results | Weigthed values | Advised LoA |
|---|---|---|---|---|---|---|
| Number of variability sources | 10 | Tension, distances, allignment, positions, cont | 3,00 | 10 | 0,3 | |
| Interval of variability | Unknown | Operators use experience | 11,20 | 10 | 1,12 | |
| Diversification | 2 | Two slightly different products | 3,10 | 2 | 0,062 | |
| Interdependency | Independent | | 1,80 | 10 | 0,18 | |
| Number of variability sources | 10 | Tool aging, and various supply errors | 3,00 | 10 | 0,3 | |
| Interval of variability | Unknown | Operator uses own judgement | 11,20 | 10 | 1,12 | |
| Diversification | 3 | Different materials and tools that can get error | 3,10 | 3 | 0,093 | |
| Interdependency | Independent | | 1,80 | 10 | 0,18 | |
| Number of alternatives | 3 | Three operators with slightly different ways | 2,10 | 3 | 0,063 | |
| Number of actions | 1 to 5 (low) | | 1,50 | 0 | 0 | |
| Patterned actions | Some actions patterned | | 2,00 | 0 | 0 | |
| Concurrency | Concurrent | Operator concurrently controls sequence, dist | 6,40 | 5 | 0,32 | |
| Time availability | Sufficient | Always | 21,00 | 0 | 0 | |
| Sensorial | 2 | Tactile and eyes | 4,70 | 2 | 0,094 | |
| Cognitive requisite | Yes | Humans make adjustments to guidelines with p | 14,00 | 10 | 1,4 | |
| Physical prerequisite | Yes | Recently employee removed from task | 10,10 | 10 | 1,01 | |
| | | | 100,00 | 95 | 6,242 | |
| | | | | | Moderate | 5 |

Figure 10: In- and output in framework for Assembly

To summarize, the results of the framework do align for the Filling mould I task. However, for the Assembly task the framework does not align with the expected outcomes at VDL. By adjusting parameters weights or possibly exclude parameters from the framework due to their relevance we can align the framework with the expected outcomes. We advise to consider the parameter of time availability for exclusion, while the number of variability sources could potentially be given greater importance. These adjustments enhance the framework's applicability and effectiveness in optimising processes at VDL. We also recommend applying the adjusted framework to other tasks to validate the revised parameter settings.

# 5 Economic and non-economic impact

In this chapter we incorporate the analysis phase (Section 2.1.2) into the decision-making process, by answering Research question 3:

> "Which decision-making approaches suit best to facilitate decision-making for the manufacturing process of product X?"

Section 5.1 analyses the non-economic benefits that can be achieved through automation in the manufacturing process. Section 5.2 determines the economic impact of automation.

## 5.1 Non-economic benefits

Non-economic benefits can be difficult to express in terms of direct costs. We address Sub question 3.1:

> "How can we determine the non-economic impact of automation opportunities for VDL?"

The non-economic benefits identified in Section 3.1.3 primarily include ergonomic and quality improvements. We identify insufficient quality of supply as the main cause of quality issues in the manufacturing process of product X. Automation is beneficial for preventing quality issues caused by operators. However, quality issues caused by insufficient quality of supply is difficult to solve with automation, because the tools have to be programmed to identify (unpredictable) irregularities. Consequently, improvement of quality is not considered as an non-economic benefit in the manufacturing process of product X.

In Section 3.1.3, we also discuss that no data indicates ergonomic issues, but this does not mean such occurrences will not happen in the future. In the process variability framework we identify physical demanding tasks for the parameter 'Physical requirements'. Physically demanding tasks, increase process variability due to operators more likely to lose concentration and control, causing the process variability framework to recommend a lower LoA. However, if we identify that there is a physical requirement it is crucial to assess the physical demand the task has on employees. In conclusion, even if the process does not technically (according to guidelines) pose ergonomic issues, this could be the decisive factor in automation decision-making.

## 5.2 Economic impact

By addressing the ultimate requirement, profitability, we tackle Sub question 3.2:

> "How can we determine the economic impact of automation opportunities for VDL?"

As we discuss in Section 2.4, assessing process variability assists in determining the maximum LoA that is economically feasible. In this section we develop the final tool that aids in the decision-making process, by incorporating the LoA assessment (Section 3.3), variability framework and viable cost reductions. In Section 5.2.1 we outline the method for determining viable cost reductions, followed by Section 5.2.2, where we combine all factors in the final tool.

### 5.2.1 Potential cost reduction

#### *Bottlenecks and capacity*

Based on factory physics discussed in Section 2.2.3 bottlenecks should be addressed in the manufacturing process of product X to effectively reduce cycle time. Sometimes expensive stations or tasks in a manufacturing process can be beneficial as bottlenecks, with their variability being managed by cheaper steps with low utilization. However, in Section 3.2 we conclude that there is no variation in hourly cost rate in the manufacturing process of product X, which is why we want to address bottlenecks. We identify bottlenecks with the following formulas:

$$\text{Throughput rate} = \frac{Demand\ per\ week}{Hours\ per\ week}$$

$$\text{Utilization} = \frac{Throughput\ rate}{Production\ rate\ per\ machine}$$

Additionally, in consultation with the company, we discovered that the maximum capacity number is a useful indicator for VDL to understand when the company must take action. The maximum capacity indicates at which throughput rate the utilization is 100%. Maximum capacity allows VDL to easily identify potential bottlenecks as demand grows and set a minimum capacity as a constraint.

Table 7 presents the utilization and capacity (scaled by a factor as detailed in Appendix G) of each task in the manufacturing process of product X. Currently, the process is not operating at full capacity and does not face capacity issues. However, the changing industry can rapidly increase demand, and the company needs to be able to reach this demand aligning with the company's goals to remain market leader. In Table 7, we identify the task 'Assembly' as bottleneck. With an utilization of 83% this task determines the maximum throughput rate for the entire manufacturing line and could become critical when anticipating potential rapid increases in demand. Additionally, due unavoidable process variability, it is undesirable to achieve full utilization, as this could lead to system overload.

Table 7: Utilization and capacity

| Production step | Utilization (per machine) | Capacity (Scaled production volume per week) |
|---|---|---|
| Filling mould I | 0,085417 | 1170 |
| Glue I | 0,607917 | 160 |
| Mark I | 0,183333 | 545 |
| Route | 0,125 | 800 |
| Manifold block I | 0,041667 | 2400 |
| Forming curves | 0,375 | 265 |
| Mark II | 0,141667 | 705 |
| Manifold block II | 0,166667 | 600 |
| Filling mould II | 0,0625 | 1600 |
| Glue II | 0,689028 | 145 |
| Leak testing | 0,6875 | 145 |
| Assembly | 0,833333 | 120 |
| Adjustment | 0,166667 | 600 |

### *Cycle time constraint*

This research originates from the T&D department, where the creation of new automation solutions is relatively expensive compared to automation implemented by factory engineers on the factory floor. Therefore, for a task to be considered worthwhile for automation by the T&D department, there must be a significant potential for cost reduction. A cost reduction of a few euros per product is insufficient to justify their involvement. Based on discussions with VDL and considering the hourly cost rate in the manufacturing process, we conclude that an investment in automation only becomes interesting if there is a potential cycle time reduction of at least one hour.

In Section 3.2, we identify the cycle time and waiting time for each task. By subtracting the (nearly) unavoidable waiting times from the cycle times, we can assess the potential cycle time reductions per task against the one-hour constraint. Tasks with short cycle times or long waiting times are less attractive for automation. However, if one investment can be applied to multiple tasks, it enhances the overall potential reduction in cycle time.

In conclusion, to determine the viable cost reduction we incorporate potential effective cycle time reduction in the final tool. We calculate if the potential cycle time reduction is sufficient, considering the one-hour constraint and address tasks with a high utilization.

## 5.2.2 The final tool

With the development of a tool we support objective decision-making for automation in high-tech, low-volume manufacturing processes. The tool indicates whether automation is appropriate by highlighting red cells, focussing on economic viability. If all outputs of the calculated objectives turn red, it strongly suggests that the LoA should be increased. This situation typically highlights opportunity for automation, opportunity for big cycle time reduction, tasks with a high utilization (potential bottleneck) and low process variability.

Outputs of the tool are categorized in ‘minimum required LoA’ and ‘Advice’. The left side of the tool provides the minimum required LoA. As depicted in Figure 11 the tool highlights cells red in the "Min difference" column. Red cells indicate that the current LoA is below the minimum required LoA to produce products of sufficient quality (Section 3.3). Therefore, those sub tasks must be automated at least until the minimum difference is zero.

| Tasks | | Levels of Automation | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | | Mechanical and equipment | | | | | Information and control | | | | |
| Task | Task description | Current estimate | Min | Min difference | Max | Max difference | Current estimate | Min | Min difference | Max | Max difference |
| | **Filling mould I** | | 2 | | 6 | | | 3 | | 6 | |
| 1 | Select variant | 0 | 0 | 0 | 0 | 0 | 1 | 1 | 0 | 6 | 5 |
| 2 | Check product | 1 | 1 | 0 | 6 | 5 | 1 | 3 | -2 | 6 | 5 |
| 3 | Hold together | 2 | 2 | 0 | 6 | 4 | 0 | 0 | 0 | 0 | 0 |

Figure 11: The minimum LoA

In the right side of the tool, the 'Advice' column presents the incorporated decision-making factors. The advice is categorized into two parts: viable investment costs and viable cost reduction. Viable investment costs refer to the investment expenses that are practical, justifiable, and sustainable over time, given the current LoA, maximum LoA and the recommended maximum LoA, based on the variability framework. The tool evaluates the viable investment costs by comparing the recommended maximum LoA with the current and maximum LoA. We assess the viable cost reduction by evaluating if the potential savings are practical and sustainable over time, considering potential yield in cycle time reduction. Figure 12 presents a detailed picture of the tool, with advice for the Assembly task. We insert the advised LoA obtained from the variability framework in the insert column. The tool highlights many cells red, indicating sub tasks that show beneficial opportunities in automation, because of viable investment costs and cost reduction. If only three out of the four columns turn red, the decision depends on the relative importance of each factor to the company.

| **Tasks** | **Insert** | **Advice** | | | | |
|---|---|---|---|---|---|---|
| | | **Viable investment costs** | | **Viable cost reduction** | | |
| Task description | LoA advice based on process variability | M&E LoA increase | I&C LoA increase | Automate **only** this task? | Utilization | Comments |
| **Assembly** | | | | | 83,33% | |
| Check for dirt | 5 | 0 | 0 | FALSE | | |
| Orient product correctly | 5 | 4 | 2 | TRUE | | |
| Place a mat | 5 | 4 | 2 | TRUE | | |
| Make a decision | 5 | 3 | 2 | TRUE | | |
| Tighten and loosen screws | 5 | 2 | 2 | TRUE | | |
| Apply Fomblin | 5 | 3 | 2 | TRUE | | |
| Place stickers | 5 | 4 | 2 | TRUE | | |
| Install tie wraps | 5 | 4 | 2 | TRUE | | |
| Cut ties | 5 | 3 | 2 | TRUE | | |
| Install earth cable | 5 | 3 | 2 | TRUE | | |
| Placing strain reliefs | 5 | 0 | 0 | FALSE | | |
| Attach strain relief to CSI hood | 5 | 0 | 0 | FALSE | | |
| Place hoses in trench | 5 | 0 | 0 | FALSE | | |
| Mount manifold on CSI | 5 | 0 | 2 | TRUE | | |
| Route product | 5 | 0 | 0 | FALSE | | |
| Place top and cover plate | 5 | 3 | 0 | TRUE | | |
| Installing product assemblies | 5 | 3 | 0 | TRUE | | |

Figure 12: Tool output of the task 'Assembly'

VDL can customize the tool to their needs, by adjusting factors such as cycle time and maximum capacity constraints. Additionally, weights, parameters and values of the parameter states can be adjusted in the process variability framework.

# 6 Conclusion and future work

In Section 6.1, we address the main research question:

"How can VDL determine which tasks in the high-tech, low-volume manufacturing and assembly process should be optimised with automation?"

Additionally, we provide a discussion with recommendations in Section 6.2.

## 6.1 Conclusion

In conclusion, with the development of a tool we provide valuable insights to guide the investment decision-making process. We assess the viable investment costs with the use of a process variability framework discussed in Chapter 4. This framework provides an advice on the maximum LoA to implement in high-tech, highly manual manufacturing processes. Additionally we conduct an automation opportunity assessment through comparison with the current and maximum LoA estimate, which is obtained with the DYNAMO method (Section 3.3). Furthermore, we assess the viable cost reductions, by looking at possible cycle time reductions, taking bottlenecks and the hourly cost rate into account (Section 5.2). In the final decision-making phase (Section 2.1.2) it is up to VDL to integrate this tool into their continuous improvement efforts and make the final decisions regarding selection of automation opportunities.

## 6.2 Discussion and recommendations

In Section 6.2.1 we provide recommendations for optimisation opportunities. Subsequently, we provide a discussion and recommendations on the final tool in Section 6.2.2 and on the variability framework in Section 6.2.3.

### 6.2.1 Reduce waste before automation

As discussed in Section 3.1.1, many improvement concepts at VDL remain in the early stages. Before investing in automation we recommend VDL to evaluate optimisation opportunities, by focussing on CIP and incorporating Lean methodologies. Throughout this research, we identify opportunities where cost-effective optimization can be achieved without automation.

#### *Optimisation efforts*

VDL focusses on standardization, by updating quality reports, which include guidelines for operators. These adjustment help clarify the best practices and eliminate unnecessary variability. However, some reports for the manufacturing process of product X are still outdated. Updating these is potentially more cost effective for optimization than investing in automation.

Besides standardization, VDL identifies waste with the Lean Six Sigma method. VDL incorporates a Standard Working Sheet of the manufacturing process of product X, which visualizes the current operator and product flows (VDL, 2023a). This sheet clearly shows that for example, operators walk in an inefficient manner, because of the position of the workstations. Before investing in automation we advise to eliminate non-value-adding tasks, including unnecessary movements of materials and operators. These improvements may involve reconfiguring the cleanroom and workstations[2].

*The supply chain*

The quality of supplied materials is a critical issue in the manufacturing of product X, leading to high variability in both product quality and the manufacturing process. The materials often exhibit irregularities such as contamination or expired dates. Moreover, the reliability of the supply chain itself is questionable, sometimes the production process cannot continue due to missing materials, leading to outages and waiting times during the manufacturing process. While automation can address these challenges by increasing capacity, identifying quality issues in materials is complex, requiring high investments. Improving material supply may be more efficient, potentially through negotiating better agreements with current suppliers or considering alternative suppliers.

*Work rate variability*

The working speed of employees is influenced by various factors such as experience, motivation, and age, which contribute to natural human variability and cannot be completely eliminated. This variability does not impact outputs, however, reducing this variability can be more cost effective for reduction of cycle times, than investing in automation. This can be achieved through better education, training, and standardisation in the manufacturing processes of product X.

### 6.2.2 The tool

The T&D department desires a simple and relatively fast way to assess the optimal LoA. While we can develop more accurate methodologies, such as modelling, they can be complex and time-consuming, as discussed in Section 2.2.2.

Due to time constraints, we are unable to apply the tool and framework to all tasks in the manufacturing process of product X. However, for comprehensive automation decision-making all tasks should be evaluated with the variability framework and developed tool. We advise fine-tuning of the variability framework (Section 6.2.3) and then applying the framework and tool to all tasks. Further validation can be done by evaluating the recommended investments. Additionally, we recommend integrating the tool with other methods to ensure active use and to enhance decision-making with valuable input from these methods.

Additionally, validating the tool, by evaluating investments could take several years. VDL experts should periodically assess whether the recommended investments are viable, economically beneficial and evaluate the tool's ease of use. For example, by gathering feedback from users and data on the selected investments and their achieved reduction in cycle time.

[2]Challenges can arise, such as specialized exhaust pipes that are fixed in place, preventing the relocation.

### 6.2.3 The variability framework

We recommend fine-tuning of the variability framework. In the variability framework, we utilize weights assigned by experts from literature. However these weights are obtained with a AHP tool, which indicates inconsistency in the comparison of parameters (Section 4.2). The assigned weights are subjective, VDL should involve multiple experts that assign their own weights, while passing the consistency check.

Furthermore, the parameters of process variability have proven difficult and time consuming to understand and are sometimes interpreted differently. Multiple company experts should collaboratively explore and define their understanding of process variability parameters, increasing consistency. Through discussion, they can determine which parameters should be retained or added to the tool for the manufacturing process of product X. We also advise to designate one or a few experts at VDL to utilize the framework in practice. They can become the experts in describing process variability, ensuring a consistent and accurate advice.

Additionally, as discussed in Section 5.2, the cycle time should present opportunities for at least one hour of reduction to achieve acceptable cost yields for the T&D department. However, even when a task has a low potential for cost reduction, applying the variability framework can still prove beneficial, as it can increase the engagement of stakeholders. Involving factory engineers and floor managers in the decision-making process is crucial. To increase their enthusiasm and investment in the process, it is beneficial to implement factors that align with their interests, such as smaller automation opportunities.

Besides, automating a task in combination with another can still significantly reduce cycle time. For example, in the 'Filling Mould I' task shown in Figure 13, two out of four columns turn red, indicating that automating this task alone is not recommended due to its short cycle time and low utilization. However, if a tool can be used in multiple tasks, the investment can still prove beneficial. Additionally, we set the cycle time constraint for the costly T&D department, but minor improvements can still be interesting for factory engineers and floor managers.

| Tasks | Insert | Advice | | | | |
|---|---|---|---|---|---|---|
| | | Viable investment costs | | Viable cost reduction | | |
| Task description | LoA advice based on process variability | M&E LoA increase | I&C LoA increase | Automate **only** this task? | Utilization | Comments |
| **Filling mould I** | | | | | 8,54% | |
| Select variant | 6 | 0 | 5 | FALSE | | |
| Check product | 6 | 5 | 5 | FALSE | | e.g. Heavy task |
| Hold together | 6 | 4 | 0 | FALSE | | |

Figure 13: Tool output for task 'Filling mould I'

# Bibliography


Almannai, B., Greenough, R., & Kay, J. (2008). A decision support tool based on QFD and FMEA for the selection of manufacturing automation technologies. *Robotics and Computer-Integrated Manufacturing*, *24*(4), 501-507. https://doi.org/https://doi.org/10.1016/j.rcim.2007.07.002

Angel, S.-S. (2016). *A framework to support automation in manufacturing through the study of process variability* (https://repository.lboro.ac.uk/articles/thesis/A_framework_to_support_automation_in_manufacturing_through_the_study_of_process_variability/9521177

Barnard, S. (2016).

Bhatti, M., Awan, H., & Razaq, Z. (2014). The key performance indicators (KPIs) and their impact on overall organizational performance. *Quality & Quantity*, *48*. https://doi.org/10.1007/s11135-013-9945-y

Cavone, G., Dotoli, M., Epicoco, N., Franceschelli, M., & Seatzu, C. (2018). Hybrid Petri Nets to Re-design Low-Automated Production Processes: the Case Study of a Sardinian Bakery. *IFAC-PapersOnLine*, *51*(7), 265-270. https://doi.org/https://doi.org/10.1016/j.ifacol.2018.06.311

Cooper, R., Edgett, S., & Kleinschmidt, E. (2002). Portfolio management for new product development: Results of an industry practices study. *R&D Management*, *31*, 361-380. https://doi.org/10.1111/1467-9310.00225

Frohm, J. (2008). *Levels of automation in production systems*

Frohm, J., Lindström, V., Winroth, M., & Stahre, J. (2006). *The Industry's View on Automation in Manufacturing*. https://doi.org/10.13140/RG.2.1.2535.6006

Garcia, M. L., & Bray, O. H. (1997). *Fundamentals of technology roadmapping*. https://www.osti.gov/biblio/471364

https://www.osti.gov/servlets/purl/471364

Goh, Y. M., Micheler, S., Sanchez-Salas, A., Case, K., Bumblauskas, D., & Monfared, R. (2020). A variability taxonomy to support automation decision-making for manufacturing processes. *Production Planning & Control*, *31*(5), 383-399. https://doi.org/10.1080/09537287.2019.1639840

Groenveld, P. (2007). ROADMAPPING INTEGRATES BUSINESS AND TECHNOLOGY [Article]. *Research Technology Management*, *50*(6), 49-58. https://doi.org/10.1080/08956308.2007.11657472

Hamzeh, R., & Xu, X. (2019). Technology selection methods and applications in manufacturing: A review from 1990 to 2017. *Computers & Industrial Engineering*, *138*, 106123. https://doi.org/https://doi.org/10.1016/j.cie.2019.106123

Heerkens, H., & van Winden, A. (2017). *Solving Managerial Problems Systematically* (Vol. 135 p.). Noordhoff Uitgevers.

Hofmann, M. (2021). *A Holistic Approach to Process Optimisation*. Springer Wiesbaden. https://doi.org/https://doi-org.ezproxy2.utwente.nl/10.1007/978-3-658-34097-1

Hopp, W. J., & Spearman, M. L. (2008). *Factory physics* (3rd ed.). McGraw-Hill/Irwin/Irwin.

Hummel, S. W. B. (2019). *Creating an automation roadmap for manufacturing companies combining literature and practice to come to a decision support tool* Eindhoven University of Technology].

Liker, J. (2004). The 14 principles of the Toyota way: An executive summary of the culture behind TPS. *The Toyota Way: 14 Management Principles from the World's Greatest Manufacture*, 35-41.

Löfving, M., Almström, P., Jarebrant, C., Wadman, B., & Widfeldt, M. (2018). Evaluation of flexible automation for small batch production. *Procedia Manufacturing*, *25*, 177-184. https://doi.org/https://doi.org/10.1016/j.promfg.2018.06.072

Löfving, M., Almström, P., Jarebrant, C., Wadman, B., & Widfeldt, M. (2020, Oct 07-08). Guide for Automation of Low Volume Production.*Advances in Transdisciplinary Engineering* [Sps2020]. 9th Swedish Production Symposium (SPS), Jonkoping Univ, Sch Engn, ELECTR NETWORK.

Löfving, M., Almström, P., Jarebrant, C., & Widfeldt, M. (2023, 2023). *Design and Application of a Development Map for Aligning Strategy and Automation Decisions in Manufacturing SMEs* IFIP WG 5.7 International Conference on Advances in Production Management Systems, APMS 2023 Trondheim 17 September 2023 through 21 September 2023, http://urn.kb.se/resolve?urn=urn:nbn:se:hj:diva-62628

https://link.springer.com/content/pdf/10.1007/978-3-031-43662-8_17.pdf
Mahmoud, M. (2006). Overview of optimization. In M. M. El-Halwagi (Ed.), *Process Systems Engineering* (Vol. 7, pp. 285-314). Academic Press. https://doi.org/https://doi.org/10.1016/S1874-5970(06)80012-3
Mann, R., Mohammad, M., & Agustin, M. (2012). *Understanding Business Excellence: An awareness guidebook for SMEs*.
Pekin, A., Ozkan, G., Eski, O., Karaarslan, U., Ertek, G., & Kilic, K. (2006). *Application of the Analytic Hierarchy Process (AHP) for Selection of Forecasting Software*.
Phaal, R., Farrukh, C. J. P., & Probert, D. R. (2004). Technology roadmapping—A planning framework for evolution and revolution. *Technological Forecasting and Social Change*, *71*(1), 5-26. https://doi.org/https://doi.org/10.1016/S0040-1625(03)00072-6
Powers, G., Ruwanpura, J., Dolhan, G., & Chu, M. (2003). *Simulation based project selection decision analysis tool*. https://doi.org/10.1109/WSC.2002.1166465
Pugna, A., Negrea, R., & Miclea, S. (2016). Using Six Sigma Methodology to Improve the Assembly Process in an Automotive Company. *Procedia - Social and Behavioral Sciences*, *221*, 308-316. https://doi.org/https://doi.org/10.1016/j.sbspro.2016.05.120
Puška, A., Beganović, A., & Šadić, S. (2017). Model for investment decision making by applying the multi-criteria analysis method. *Serbian Journal of Management*, *13*. https://doi.org/10.5937/sjm13-12436
Saez, M., Barton, K., Maturana, F., & Tilbury, D. M. (2022). Modeling framework to support decision making and control of manufacturing systems considering the relationship between productivity, reliability, quality, and energy consumption [Article]. *Journal of Manufacturing Systems*, *62*, 925-938. https://doi.org/10.1016/j.jmsy.2021.03.011
Salim, R., Manduchi, A., & Johansson, A. (2020). Investment Decisions on Automation of Manufacturing in the Wood Products Industry: A Case Study [Article]. *BioProducts Business*, *5*(1), 1-12. https://doi.org/10.22382/bpb-2020-001
Taghizadegan, S. (2006). Chapter 6 - Design for Lean/Kaizen Six Sigma. In S. Taghizadegan (Ed.), *Essentials of Lean Six Sigma* (pp. 59-101). Butterworth-Heinemann. https://doi.org/https://doi.org/10.1016/B978-012370502-0/50008-4
Theisens, H. C., Meek, A., & Harborne, D. (2018). *LEAN SIX SIGMA*

*GREEN BELT SKILL SET*. https://www.symbol.nl/wp-content/uploads/2020/08/180704-Skill-set-Lean-Six-Sigma-Green-Belt-v2.4-1.pdf
Tortorella, G. L., Narayanamurthy, G., & Thurer, M. (2021). Identifying pathways to a high-performing lean automation implementation: An empirical study in the manufacturing industry [Article]. *International Journal of Production Economics*, *231*, Article 107918. https://doi.org/10.1016/j.ijpe.2020.107918
Van Erp, T., Rytter, N. G. M., Sieckmann, F., Larsen, M. B., Blichfeldt, H., & Kohl, H. (2021). Management, Design, and Implementation of Innovation Projects: Towards a Framework for Improving the Level of Automation and Digitalization in Manufacturing Systems. 2021 9th International Conference on Control, Mechatronics and Automation, ICCMA 2021,
VDL. (2015). VDL QRC assy.
VDL. (2023a). *ETG Almelo Operational Excellence*. Retrieved 31-5-2024 from https://portal.vdlnet.nl/company/etgalmelo/OpEx/SitePages/Home.aspx
VDL. (2023b). Flow chart Product X. *VDL ETG Almelo T&D*.

VDL. (2023c). Quality Manual VDL ETG.

VDL. (2024). VDL QRC Assemblage.

Walker, J., Childe, S., & Wang, Y. (2019). Analysing manufacturing enterprises to identify opportunities for automation and guide implementation - A review. IFAC-PapersOnLine,

Wu, K., Zheng, M., & Shen, Y. (2020). A generalization of the Theory of Constraints: Choosing the optimal improvement option with consideration of variability and costs. *IISE Transactions*, *52*(3), 276-287. https://doi.org/10.1080/24725854.2019.1632503

# Appendices

## A. Systematic Literature Review

### Problem statement

Currently quality issues are the main reason for automation in the manufacturing process of product X. The production line is highly manual and influenced by employee absenteeism. With automation, benefits such as decrease in costs and lower employee dependency can be realised. To achieve these benefits a comprehensive decision-making approach is needed, aiming at decision-making based on analysis, incorporating all relevant factors for the manufacturing process of product X.

### Research goal and research question

The overarching goal of my research is to find out how a process can be analysed to decide where to automate to decrease costs and employee dependency.

I want to answer the following knowledge question with this Systematic Literature Review:

"What decision strategies are available for implementing automation in high-tech, small scale manufacturing lines?"

This knowledge question helps to understand which methods and tools are available in literature. If there is a method/tool available I can use that for my research. On the other hand, if there is a gap I can try to fill it, by using the available literature as a theoretical framework and conducting my own research.

### Key concepts and Search terms

In order to conduct a systematic search it is necessary to identify the key concepts and potential search terms in order to improve the search strings.

| | **Key concepts** |
|---|---|
| ***1*** | Manufacturing process |
| ***2*** | Automation |
| ***3*** | Implement |
| ***4*** | Investment |
| ***5*** | Roadmap |
| ***6*** | Decision-making |
| ***7*** | Small scale |
| ***8*** | Tool |
| ***9*** | High-tech |

| | Key concepts | Related terms | Narrower terms | Broader terms |
|---|---|---|---|---|
| *1* | **Manufacturing process** | Production process | High-tech manufacturing process | Industrial process, Fabrication process, Industrial manufacturing, Manufacturing technologies |
| *2* | ***Automation*** | Mechanization, Process optimisation | Robotization, Robotics, | New technology, Industry 4.0 (fourth industrial revolution encompassing automation, data exchange, and Internet of Things) |
| *3* | ***Implement*** | | Implement technology, Implement automation | Apply, Utilize, Realize |
| *4* | ***Invest*** | Purchase | Technology investment | Put money into, Finance |
| *5* | ***Roadmap*** | Guide, Strategy, Pathway, Framework, Course of action, | Implementation plan, Decision-making tool, structured approach | Plan, Outline, approach |
| *6* | **Decision-making** | Decision, Selection | Strategic decision-making, Structured decision-making | Critical thinking, Management |
| *7* | ***Small scale*** | Low volume | Small batch manufacturing | |
| *8* | ***Tool*** | Instrument, Aid | Decision-making tool | Means |
| *9* | ***High-tech*** | Advanced-, Modern-, innovative-technology, Advanced engineering | Technology, Tech sector | Semiconductor technology |

## Inclusion and exclusion criteria

| Inclusion criteria | Exclusion criteria |
|---|---|
| *Size of production: Small batch. Implementing automation in mass-production has another focus and perspective than manufacturing of small batch production.* | Exclude when there is **no** focus on costs, employee dependency or quality. For example articles that specifically aim at environmental or ergonomic factors. |
| *Of course for the SLR the source should be scientific coming from a data base. (selection below)* | System "**integration**" or "**implementation**", because the question is not on how to implement the new technologies but "**where**". |

## Databases

| Source | Motivation or justification to use this source |
|---|---|
| **Web of science** | Large multidisciplinary database with scientific articles |
| **Scopus** | Large multidisciplinary database with scientific articles |
| **Business Source Complete** | Specialized database: Contains business related topics. |
| **Emerald Publishing** | Specialized database: Contains specific sources on business, management and engineering. |
| **ScienceDirect** | It is a publisher-specific database with a lot of scientific multidisciplinary sources. |

## Search log

| Date | Source | Search string (databases) or search method (other sources) | Total hits | Remarks |
|---|---|---|---|---|
| ***12-4-2024*** | *Scopus* | ( manufacturing OR production ) AND ( invest* OR implement* ) AND ( automation OR "new technology*" ) AND ( LIMIT-TO ( LANGUAGE , "Dutch" ) OR LIMIT-TO ( LANGUAGE , "English" ) ) | 379,028 | *I did not really get what I wanted.* |
| ***12-4-2024*** | Scopus | ( manufacturing OR production ) AND ( invest OR implement ) AND ( automation OR "new technology" ) AND ( LIMIT-TO ( LANGUAGE , "Dutch" ) OR LIMIT-TO ( LANGUAGE , "English" ) ) | 28,469 | Without stars |
| ***12-4-2024*** | Scopus | ( manufacturing OR production ) AND ( invest OR implement ) AND ( automation ) AND ( decision-making ) AND ( LIMIT-TO ( LANGUAGE , "Dutch" ) OR LIMIT-TO ( LANGUAGE , "English" ) ) | 4,396 | Still a lot what I do not want |
| ***12-4-2024*** | Scopus | TITLE ( ( manufacturing OR production ) AND ( invest OR implement ) AND ( automation ) AND ( decision-making ) ) AND ( LIMIT-TO ( LANGUAGE , "Dutch" ) OR LIMIT-TO ( LANGUAGE , "English" ) ) | 0 | |
| ***12-4-2024*** | Scopus | TITLE ( ( manufacturing* OR production* ) AND ( invest* OR implement* ) AND ( automation OR "New technologies*" ) ) AND ( LIMIT-TO ( LANGUAGE , "Dutch" ) OR LIMIT-TO ( LANGUAGE , "English" ) ) | 52 | This is nice!<br>I got a lot of articles containing information about implementing automation in manufacturing processes. |

| | | | | |
|---|---|---|---|---|
| ***12-4-2024*** | Scopus | TITLE ( ( manufacturing* OR production* ) AND ( Framework OR Roadmap) AND ( automation OR "New technologies*" ) ) AND ( LIMIT-TO ( LANGUAGE , "Dutch" ) OR LIMIT-TO ( LANGUAGE , "English" ) ) | 18 | Interesting sources already found by the search query above. |
| ***12-4-2024*** | Scopus | TITLE ( ( manufacturing* OR production* ) AND ( Systematically) AND ( automation OR "New technologies*" ) ) AND ( LIMIT-TO ( LANGUAGE , "Dutch" ) OR LIMIT-TO ( LANGUAGE , "English" ) ) | 0 | |
| *12-4-2024* | Scopus | TITLE ( ( manufacturing* OR production* ) AND ( “employee dependency”) AND ( automation OR "New technologies*" ) ) AND ( LIMIT-TO ( LANGUAGE , "Dutch" ) OR LIMIT-TO ( LANGUAGE , "English" ) ) | 0 | |
| *12-4-2024* | ScienceDirect | TITLE ( ( manufacturing OR production ) AND ( invest OR implement) AND ( automation OR "New technologies" ) ) AND ( LIMIT-TO ( LANGUAGE , "Dutch" ) OR LIMIT-TO ( LANGUAGE , "English" ) ) | 2,804 | Too many results. |
| *12-4-2024* | ScienceDirect | Title, abstract, keywords: ( ( manufacturing OR production ) AND ( invest OR implement ) AND ( automation OR "New technologies" ) ) | 1,868 | Still too many. |
| *12-4-2024* | ScienceDirect | Title, abstract, keywords: manufacturing AND ( invest OR implement ) AND ( automation OR "New technologies" )<br><br>+ Included terms: roadmap, decision-making, automation, investment | 37 | Better sources, after searching not a lot of relevant sources found, or duplicates of Scopus. |
| *12-4-2024* | Web of Science | TITLE ( ( manufacturing OR production ) AND ( invest OR implement) AND ( automation OR "New technologies" ) ) | 17 | Very random, selection on “Title” doesn’t work. |
| *12-4-2024* | Web of Science | Invest automation manufacturing (Roadmap OR Decision-making) | 29 | Found one relevant source, but different queries do not deliver others. |
| *12-4-2024* | Business Source Complete | TITLE ( ( manufacturing) AND (decision making or decision-making or decision making process or decision-making process) AND ( automation) ) | 1 | Nice source. |
| *12-4-2024* | Emerald Publishing | ( manufacturing) AND ( automation) AND (decision making or decision-making or decision making process or decision-making process) AND (roadmapping or roadmap or strategy) | 87 | Interesting sources some are not useful, because they are too focused on one subject. |

## Screening of sources

1. First selection on Title.
2. Secondly, selection on abstract and citation to endnote.
3. Then I removed all duplicates (the ones containing the least information) through EndNote.
    a. Library –> Find duplicates.
    b. First, the group contained 18 sources, after removing all duplicates my list contained 13 sources.
4. Finally the full text needs to be analysed in order to make the conceptual matrix and answer the knowledge question.
    a. Read full text
        i. When reading text of the articles, sometimes other relevant sources popped up. Through snowballing new sources where added to the SLR.
        ii. Once, looking up the author also delivered a new relevant source.
    b. Decide on the final set of articles to include.

## Conceptual matrix

Organized on different concepts, the sources are ordered in the matrix below. Different ways and approaches on creating an automation roadmap are considered in the concepts of the sources. The sources have for example different approaches on calculating and prioritising benefits in the cost/benefit ratio of automation investment options.

| Articles / Topics | Road mapping | Lean (delete waste) | LoA /Automation possibilities | Intangible benefits automation | RoI/ economic benefits | Modelling | Extra |
|---|---|---|---|---|---|---|---|
| (Löfving et al., 2020) | X | X | X | | X | | |
| (Löfving et al., 2023) | X | | | | | | Found by looking up other articles of Löfvingo. |
| (Walker et al., 2019) | | X | | | X | | Review, interesting sources for snowballing. |
| (Van Erp et al., 2021) | X | | X | | | | |
| (Tortorella et al., 2021) | | X | | X | X | | |
| (Salim et al., 2020) | X | | X | X | X | | |
| (Saez et al., 2022) | X | | | X | X | X | |
| (Phaal et al., 2004) | X | | | | | | Found through snowballing. |
| (Almannai et al., 2008) | X | X | | X | | | Found through snowballing. |
| (Cavone et al., 2018) | X | | | | X | X | |
| (Groenveld, 2007) | | | | | | | Found through snowballing. |

| | | | | | | | |
|---|---|---|---|---|---|---|---|
| **(Garcia & Bray, 1997)** | x | | | | | | Found through snowballing. |

In table 8 we identify limitations of the sources from the SLR.

Table 8: Literature gap

| Name | Author, year | Topic | Limitations (gap to fill) |
|---|---|---|---|
| Design and Application of a Development Map for Aligning Strategy and Automation Decisions in Manufacturing SMEs | (Löfving et al., 2023) | To better understand how automation fits strategically and aligns with investment decisions in manufacturing SMEs. | Very broad and only focussed on aligning strategy with automation decisions.<br>VDL is not a SME, on the other hand the production process is low volume. |
| Guide for Automation of Low Volume Production | (Löfving et al., 2020) | There is a guide developed, but complete guide (a website) only in Swedish. Article does show evaluation of guide use.<br>Link to website: https://www.edig.nu/swedprod | Language (Mailed author and some other people, but haven't heard back.) |
| Analysing manufacturing enterprises to identify opportunities for automation and guide implementation - A review | (Walker et al., 2019) | Review, on available sources. highly focused on identifying interesting directions for further research. | Not focused on low automated process.<br>Only focus on economic factors and efficiency.<br>It is a review and does not contain a roadmap and is highly focused on modelling manufacturing process. |
| Hybrid Petri Nets to Re-design Low-Automated Production Processes: the Case Study of a Sardinian Bakery | (Cavone et al., 2018) | Show how first-order hybrid Petri nets can efficiently re-design low-automated production systems, using a bakery case study to identify and evaluate solutions for meeting increased market demand for "pane Carasau" | Only focused on efficiency.<br>Not an high-tech manufacturing line. |
| Identifying pathways to a high-performing lean automation implementation: An empirical study in the manufacturing industry | (Tortorella et al., 2021) | Research on sequence of implementing Lean Management and Automation. Pathways to optimally perform Lean Automation. | Not focused on creating a roadmap. Concludes that companies benefit from clear guidelines on implementing automation and lean management, helping them prioritise efforts and focus, but lacks the guidelines itself. |
| Investment Decisions on Automation of Manufacturing in the Wood Products Industry: A Case Study | (Salim et al., 2020) | The paper focussed on aspects to consider in the process leading to investment decisions. Contains identification of the weak points in the decision process. It is a case study mainly focused on Wood industry. | Different industry: Wood industry. (High competitiveness)<br>Not really a roadmap, only what to consider in the decision-making, but not how. |
| Fundamentals of technology roadmapping | (Garcia & Bray, 1997) | Focus on the process of a technology roadmap. | Very broad. And again missing the how, in certain steps. |
| Management, Design, and Implementation of Innovation Projects: Towards a Framework for Improving the Level of | (Van Erp et al., 2021) | Discussion on efforts towards a framework that helps SME with managing and implementing innovation projects to enhance digitalization and | The roadmap is highly focused on digitalization, and on implementing a new manufacturing system, which is not asked and out of the scope. |

| | | | |
|---|---|---|---|
| Automation and Digitalization in Manufacturing Systems | | automation. Including the use of DEV-OPS cycle and OKRs. | |
| Technology roadmapping—A planning framework for evolution and revolution | (Phaal et al., 2004) | An overview of technology roadmapping. And a introduction of a fast-start method developed by autohors to address the gap in roadmapping. | Relevant source for an overview on roadmapping strategies, but very standard, more detail is needed. |
| A decision support tool based on QFD and FMEA for the selection of manufacturing automation technologies | (Almannai et al., 2008) | This paper outlines an automation decision-making tool, that uses two techniques: quality function deployment (QFD) and failure mode and effects analysis (FMEA). | Not focused on investment costs, but only on risks and opportunities. |
| Modeling framework to support decision making and control of manufacturing systems considering the relationship between productivity, reliability, quality, and energy consumption | (Saez et al., 2022) | This article provides a framework for modeling and optimising manufacturing systems, exemplified through a case study in a fully automated testbed, emphasizing productivity, reliability, quality, and energy consumption. | Framework on modelling not on the decision-making process itself.<br>Lacks factors such as labour dependency. |

## B. Formulas cycle Time, Utilization, Bottleneck and Variation

m = $number\ of\ (identical)\ machines\ at\ station$

u(m) = $utilization\ of\ station\ with\ m\ machines\ installed$

CT(m) = $cycle\ time\ at\ station\ with\ m\ machines\ installed$

$c_a$ = $coefficient\ of\ variation\ of\ arrivals\ to\ station$

$c_d$ = $coefficient\ of\ variation\ of\ departures\ from\ station$

$t_e = mean\ effective\ process\ time\ for\ machine\ per\ product, including\ outages, setups\ rework, and\ other\ routine\ disruptions\ in\ hours$

$r_e = \frac{1}{t_e} = effective\ production\ rate$

$t_a$= $mean\ time\ between\ arrivals$

$r_a = \frac{1}{t_a} = arrival\ rate\ (throughput)$

$r_b = bottleneck\ rate$

1) $u = \frac{r_a}{r_e}$
2) $r_b = \frac{parts}{hour}\ of\ workstation\ with\ highest\ u$
3) $CT = CT_{que} + t_e = \left(\frac{c_a^2+c_e^2}{2}\right)\left(\frac{u}{1-u}\right) t_e + t_e$

In case there are multiple machines at a station:

4) $u(m) = \frac{r_a}{m*r_e}$
5) $CT(m) = \left(\frac{c_a^2+c_e^2}{2}\right)\left(\frac{u^{\sqrt{2(m+1)}-1}}{m(1-u)}\right) t_e + t_e$

In formula 3 the total cycle time adds up the effective process time and the queuing time. The first part between brackets calculates the variation to include in the average queuing time.

The formula for the coefficient of variance is:

$$c = \frac{\sigma(variance)}{t(mean)}$$

For instance, if a station usually takes 15 minutes to process a job, but once every 50 jobs it takes 17 times longer ($15 * 17 = 255$ minutes). The mean is $15 * 49 + \frac{255}{50} = 19.8$ minutes per job. The variance is then 4.8 minutes, leading to c= 2.5, which is a high variation according to table 9.

Table 9: variability categorized in classes by Hopp & Spearman (2008)

| Variability class | Coefficient of variation | Typical situation |
|---|---|---|
| Low | $c < 0.75$ | Process times without outages |
| Moderate | $0.75 < c < 1.33$ | Process times with short adjustments (e.g., setups) |
| High | $c \geq 1.33$ | Process times with long outages (e.g., failures) |

# C. AHP Tool

## C.1 Validation

Results from the Excel template (Barnard, 2016) yield the same results as Expert 1 from literature (Angel, 2016). However, according to the consistency check of this tool, which has a maximum of 10%, the comparison of parameters is not consistent as depicted in Figure 14.

| | AHP | | Consistency check |
|---|---|---|---|
| 1 | 0,051 | 5,1% | Check your results |
| 2 | 0,064 | 6,4% | 12% |
| 3 | 0,201 | 20,1% | |
| 4 | 0,021 | 2,1% | |
| 5 | 0,017 | 1,7% | |
| 6 | 0,017 | 1,7% | |
| 7 | 0,017 | 1,7% | |
| 8 | 0,046 | 4,6% | |
| 9 | 0,234 | 23,4% | |
| 10 | 0,058 | 5,8% | |
| 11 | 0,137 | 13,7% | |
| 12 | 0,137 | 13,7% | |
| 13 | 0,000 | ~~0,0%~~ | |
| 14 | 0,000 | ~~0,0%~~ | |
| 15 | 0,000 | ~~0,0%~~ | |

Figure 14: AHP tool validation

## C.2 VDL Expert 1

As shown in Figure 15, the first engineer who filled in the weights did not pass the consistency check, similar to the first expert from the literature. However, the engineer's results show an additional 10% increase in inconsistency. Figure 15 illustrates these findings.

| | AHP | | Consistency check |
|---|---|---|---|
| 1 | 0,063 | 6,3% | Check your results |
| 2 | 0,055 | 5,5% | 22% |
| 3 | 0,082 | 8,2% | |
| 4 | 0,031 | 3,1% | |
| 5 | 0,086 | 8,6% | |
| 6 | 0,149 | 14,9% | |
| 7 | 0,016 | 1,6% | |
| 8 | 0,023 | 2,3% | |
| 9 | 0,135 | 13,5% | |
| 10 | 0,142 | 14,2% | |
| 11 | 0,095 | 9,5% | |
| 12 | 0,124 | 12,4% | |
| 13 | 0,000 | ~~0,0%~~ | |
| 14 | 0,000 | ~~0,0%~~ | |
| 15 | 0,000 | ~~0,0%~~ | |

Figure 15: Results AHP tool VDL Expert 1

## C.3 VDL Expert 2

Figure 16 presents the results from the second VDL expert. This expert, who is both an engineer and actively involved in Lean management at the company, provided valuable insights. He emphasizes the importance of the parameter 'number of alternatives' in decision-making. From his lean management perspective, all processes should be standardized first, eliminating the need for alternatives.

| | AHP | | Consistency check |
|---|---|---|---|
| 1 | 0.054 | 5.4% | Consistency OK |
| 2 | 0.027 | 2.7% | 0% |
| 3 | 0.027 | 2.7% | |
| 4 | 0.027 | 2.7% | |
| 5 | 0.260 | 26.0% | |
| 6 | 0.108 | 10.8% | |
| 7 | 0.054 | 5.4% | |
| 8 | 0.054 | 5.4% | |
| 9 | 0.054 | 5.4% | |
| 10 | 0.108 | 10.8% | |
| 11 | 0.170 | 17.0% | |
| 12 | 0.054 | 5.4% | |
| 13 | 0.000 | ~~0.0%~~ | |
| 14 | 0.000 | ~~0.0%~~ | |
| 15 | 0.000 | ~~0.0%~~ | |

Figure 16: Results AHP tool VDL Expert 2

# D. Parameter states and corresponding values

| Parameter | States | Value |
|---|---|---|
| Quantity | - | Not applicable (0) to 10 |
| Interval of variability | Not Applicable | 0 |
| | Known | 0 |
| | Unknown | 10 |
| Diversification | - | Not applicable (0) to 10 |
| Interdependency | Not Applicable | 0 |
| | Dependent | 5 |
| | Independent | 10 |
| Quantity | - | Not applicable (0) to 10 |
| Interval of variability | Not Applicable | 0 |
| | Known | 0 |
| | Unknown | 10 |
| Diversification | - | Not applicable (0) to 10 |
| Interdependency | Not Applicable | 0 |
| | Dependent | 5 |
| | Independent | 10 |
| Number of alternatives | - | Not applicable (0) to 10 |
| Number of actions | Not Applicable | Not applicable |
| | 1 to 5 (low) | 0 |
| | 6 to 15 (medium) | 5 |
| | More than 15 | 10 |
| Patterned actions | Not Applicable | 0 |
| | Some actions patterned | 5 |
| | No pattern | 10 |
| Concurrency | Not Applicable | 0 |
| | Sequence | 5 |
| | Concurrent | 10 |
| Time availability | Not Applicable | 0 |
| | Sufficient | 0 |
| | Insufficient | 10 |
| Sensorial | - | 1 to 5 |
| Cognitive requisite | Not Applicable | 0 |
| | No | 0 |
| | Yes | 10 |
| Physical prerequisite | Not Applicable | 0 |
| | No | 0 |
| | Yes | 10 |

Figure 17: Parameter states and values (Angel, 2016)

# E. Variability identification Fill mould I

Data gathering results for assigning parameter values in the process variability framework for the task Fill mould I.

## E.1 Interview Fill mould I operator

My name is Luka Beers, and I am a student at the University of Twente, pursuing a Bachelor's degree in Industrial Engineering and Management. I am conducting this interview as part of my research project. The interview involves answering some general questions about your job. The purpose of this interview is to explore how individuals adapt to and mitigate external variability in manufacturing processes. These findings are used for decision-making in automation opportunities at VDL.

Your participation in this study is entirely voluntary, and your responses will remain anonymous. Additionally, if you are uncomfortable with a question, you do not have to answer it. The findings from my research will be published after September 2024 on the University of Twente website. If you would like to receive a copy of the results or have any questions, please feel free to contact me at l.c.beers@student.utwente.nl.

**<u>Work</u>**

**How long have you been working at VDL?**

I have been working at VDL Almelo for three years, with the majority of that time spent in internships. Initially, I completed a 6-month internship, followed by a 6-month period of academic study. Subsequently, I have worked here consistently for the past two and a half years.

**How long have you been working at this task?**

I have had an education of three weeks, however I have been working in the production process for one year. Sometimes I work at this specific task, when the original operator is with vacation or sick.

**Specification of current task (e.g. ID, Name)**

Fill mould I.

**<u>Procedure</u>**

**Can you break down this step in less than or five steps?**

Select material

Fill mould

Check if material is aligned

Close mould

Move to next station

**Of the steps you have just identified, which require difficult cognitive skills? (e.g. judgements, assessments and problem solving-thinking skills)**

Almost all of them. The mould can be filled in three different sequences, depending on the label information. The operator has to concentrate if material is in the right sequence and aligned correctly. Furthermore, if material is sufficient. Sometimes it gives contamination, because it released dye or there was thickening in the product.

**<u>Job procedure</u>**

**Do you notice differences between parts? What are the most common? (e.g. dimensions, locations, contamination, length, twists/flatness)**

Thickness of material can differ, contamination, overdue material

**How do you cope with these differences?**

Asses if material needs to be removed. If so, throw away material, select new one. Or in the most extreme cases of failure in supply, when there is no other option, use of a hairdryer to reshape material and make it acceptable.

**What do you control when you are performing the task? (e.g. dimensions, shape, dirtiness, length, alignment)**

Alignment, sequence, contamination, flatness

**Every how many seconds to you check the things you control (previous question)? Worst and best case scenario. (e.g. every 5 seconds length is checked)**

- 5 seconds
- 10 to 15 seconds
- More than 15 seconds

The things controlled are constantly checked.

**Tools**

**How many different tools do you use for this task?**

Mould A, B and C are used, but actually only differ in name.

**Is the condition of the tool an issue for the job?**

- No
- Yes, every ….

Not anymore, the lid used to close differently, but nowadays the lid always closes correctly.

**Do you work differently when you feel degradation in the tool? What do you change?**

No

Yes, … (e.g. I apply more pressure or take more time for the job)

Not applicable

**Do you customize any of your tools? What do you focus on when customizing?**

- No

- Yes, (e.g. sharpness)

**What do you think is the most critical in order to comply with standards?**

Check the sequence of materials constantly

## E.2 Identification table Fill mould I

Table 10: variability identification Fill Mould I

| Variable | Attribute | Identification through observations and reports | Operator comments | Result |
|---|---|---|---|---|
| **Outputs** | **Number of variability sources** | Dirt particles - Tightness (no tension) - Flatness - Length - Fitness of the lid - Wrong sequence. | Wrong sequence - Misalignment causing poor gluing. | **2** |
| | **Interval of variability** | Do we know the acceptable interval of: - Dirt particles - Length - Flatness - Fitness of the lid, etc.? | We know the correct sequences and that any irregularity (thickness) in the material is insufficient. However, alignment issues in the product are sometimes hard to detect, leading to poor gluing. | **Unknown** |
| | **Diversification** | Mould A, B en C. | Applicable on all. | **3** |
| | **Interdependency** | If we solve the fitness of the lid, does it solve flatness? Are they dependent? | Sequence and misalignment are not related. | **Independent** |
| **Inputs** | **Number of variability sources** | Twisted/bent material - Length (too long or too short) - Dirtiness - Kinks in product - Other material irregularities - Does the mould create any variability? - Does the card with the production number create any variability? | Thickness of material can differ - Contamination (paint that comes off) - Twisted material | **3** |
| | **Interval of variability** | How straight does the material need to be? How contaminated can the product be? | If variability is detected, the material is not accepted. But the interval is unknown. No clear guidelines on acceptable | **Unknown** |

| | | | | |
|---|---|---|---|---|
| | | | levels of twists or contamination. | |
| | **Diversification** | Does it affect the tool? Does it affect the product? | Contamination can affect both the tool (mould) and the product. | **2** |
| | **Interdependency** | If the length is fixed, does it also fix the kinks in the product? Can we find independency? | Dependent, because checking if material is sufficient includes all variabilities. | **Dependent** |
| **Strategy** | **Number of alternatives** | Are there more operators? Operators often have different ways of solving variability. - Are there different paths the operator can take to address variability in Flatness of the product - Length - Contamination - Kinks – Tool? | The only difference identified between two operators is that one aligns the mould against the blue blocks on the working table while the other does not, as the mould loses stability. | **2** |
| | **Number of actions (Every verb is an action)** | 1. Feel for kinks 2. Discard 3. Replace | 1. Assess material sufficiency 2. Discard or not 3. Get new material if needed | **Smaller than 5** |
| | **Patterned actions** | If a minimum of 3 actions (verbs) are executed more than once in the same sequence during the task. | Yes, three times: fill mould by placing material, flatten material, check sequence, and close mould. | **Some action patterned** |
| **Time** | **Concurrency** | Are sources of variability introduced in the same action and managed simultaneously? | Control material for dirt, irregularities and kinks. | **Concurrent** |
| | **Time availability** | Is the time available sufficient to solve variability in tools, parts etc.? Does the operator feel time pressure? | Enough time | **Sufficient** |
| | **Sensorial** | Are eyes and tactile senses needed to detect flatness, dirt, length, kinks? Does the operator use ears, nose, or taste? | Eyes and tactile senses are used. Hearing is used for detecting if the product bumps into something or if there are cracking sounds indicating poor alignment. | **3** |
| | **Cognitive requisite** | Does the operator use their own judgment to overcome variability? For example, detecting wrong length and cutting it off. | Yes, constantly judging if material is sufficient and in the correct sequence. | **Yes** |

| | | | | |
|---|---|---|---|---|
| | **Physical demand** | Can any operator do this task regardless of physical condition? Is special force needed or does the operator feel exhausted due to physical demand? Could this be due to detailed work? | If the right method is utilized, moving the product is not physically demanding. | **No** |

# F. Variability identification Assembly

Data gathering results for assigning parameter values is the process variability framework for the task Assembly.

## F.1 Interview Assembly operator

My name is Luka Beers, and I am a student at the University of Twente, pursuing a Bachelor's degree in Industrial Engineering and Management. I am conducting this interview as part of my research project. The interview involves answering some general questions about your job. The purpose of this interview is to explore how individuals adapt to and mitigate external variability in manufacturing processes. These findings are used for decision-making in automation opportunities at VDL.
Your participation in this study is entirely voluntary, and your responses will remain anonymous. Additionally, if you are uncomfortable with a question, you do not have to answer it. The findings from my research will be published after September 2024 on the University of Twente website. If you would like to receive a copy of the results or have any questions, please feel free to contact me at l.c.beers@student.utwente.nl.

**Work**
**How long have you been working at VDL?**
4 years
**How long have you been working at this task?**
Can do every step in process and regularly controls all steps as floor manager.
**Specification of current task (e.g. ID, Name)**
Assembly

**Procedure**
**Of the steps you have just identified, which require difficult cognitive skills? (e.g. judgements, assessments and problem solving-thinking skills)**
Continuous need of checking everything.

**Are there actions that not every person can do, because of heavy lifting, very detailed work or physical demanding jobs?**
Assembly can be quite demanding because you have to lift and pull on the cables multiple times during strain relief. Additionally, you need to be extremely careful throughout the process. One employee was recently placed on another task due to the physical demands involved.

**<u>Job procedure</u>**

**Do you notice differences between parts? What are the most common? (e.g. dimensions, locations, contamination, length, twists/flatness)**

Due to constant monitoring and inspection of the product, it always meets the requirements when it comes out. However, through these checks, we address issues such as loose screws, damages, and dimensions that are not or incorrectly specified in the manual.

**Do you notice differences between parts when another operator works on it?**

There are always certain things that operators do a bit differently, but in principle, everything should be the same.

**How do you notice variability? (e.g. sound, smell, touch etc.)**

In Assembly it is touch and eyes. Sound is also used with pressure testing, but that is after the last step, to do a last check if you hear something leaking.

**How do you cope with these differences?**

For example for the connector: unscrew, replace, close again.

**When performing a task, what aspects of the task can you control or influence? (e.g. position, sequence, shape, cleanliness, length, or alignment of something)**

Alignment, sequence, flatness, material quality, position, screw tightness, pressure, length

**Every how many seconds to you check the things you control? Worst and best case scenario.**

The things controlled are constantly checked.

**Do you feel time pressure when performing a task?**

No, I make sure there is no time pressure in the process. Supply sometimes creates trouble, however I do not let that get to the work floor.

**<u>Tools</u>**

**How many different tools do you use for this task?**

A lot of tools, such as drilling machines, strain reliefs, rulers, moulds, etc.

**Is the condition of the tool an issue for the job?**

- No
- Yes, every ….

For example, the drill bits of a drilling machine: if you have tightened 1,000 screws, you may sometimes see that the screw no longer turns, indicating that the bit needs to be replaced.

**Do you work differently when you feel degradation in the tool? What do you change?**

- No
- Yes, sometimes, when it is not yet time to replace the tool, just add a little bit of extra pressure.
- Not applicable

**Do you customize any of your tools? What do you focus on when customizing?**

- No
- Yes, (e.g. sharpness)

**What do you think is the most critical to comply with standards?**
The most critical aspect of complying with standards is ensuring clarity and specificity in the guidelines provided. While operators currently manage variability through regular checks and adjustments, the lack of clear, quantifiable rules, such as specific limits on product pressure can lead to inconsistencies.

**How does ordering new material work?**
You simply walk to the stockroom and ask if they can supply new material. Then they clean the products so they can be brought into the cleanroom. Additionally, there are also regular orders for many parts that are prepared in advance.

## F.2 Identification table Assembly

Table 11: Variability identification Assembly

| **Variable** | **Attribute** | **Identification** | **Operator comments** | **Result** |
|---|---|---|---|---|
| **Outputs** | **Number of variability sources** | Flatness – Damages – position – loose screws | Output does not differ significantly because everything is constantly checked, however if not it could have loose connectors, wrong positions of material, bad alignment, wrong distances etc. | **10** |
| | **Interval of variability** | Most of the time we know the acceptable lengths. And the right positions or when something is damaged. | For at least one source of variability, damage, we do not know the range of variability, so we do not know when the product is damaged exactly. Additionally, some things are written in the guidelines, such as lengths, but operators change these with experience, because of errors in final product. | **Unknown** |
| | **Diversification** | Two slightly different outputs. | Yes | **2** |

| | | | | |
|---|---|---|---|---|
| | **Interdependency** | Independent, because position and damage are independent. | At least one source independent. | **Indepe ndent** |
| **Inputs** | **Number of variability sources** | Damages – irregularities – contamination – missing parts in supply (Rubber rings) – Tension – sharp edges touch – sequence (accidental switches) – replacement needs of tool | Damages – sequence – flatness -lengths – distances (dotted line) – measurements – incomplete parts – tension etc. | **10** |
| | **Interval of variability** | | For at least one source unknown | **Unkno wn** |
| | **Diversification** | Does it affect tool?<br>Does it affect product? | Tools, parts from previous task and supply (material) | **3** |
| | **Interdependency** | If the length is fixed does it also fix the kinks in the product? | At least two sources are independent. | **Indepe ndent** |
| **Strategy** | **Number of alternatives** | Are there different paths the operator can take to solve:<br>The flatness of the product - The length – Contamination – Kinks - Tool | There are different operators that conduct the task. Variability is often solved with experience and own judgement and varies slightly sometimes between operators. | **3** |
| | **Number of actions (Every verb is an action)** | Check material - throw away if bad - get new material<br>Check length - change length if unacceptable - check length | Check secureness – unscrew – replace – screw back on – check secureness | **Low** |
| | **Patterned actions** | If a min of three actions (verbs) are executed more than once in the same sequence during the task. | For example checking secureness of material or screwing on thread. | **Some action pattern ed** |
| **Time** | **Concurrency** | Yes at least two sources of variability are managed at the same time | Yes, multiple sources, alignment, flatness, distances, all connected. | **Yes** |

| | | | | |
|---|---|---|---|---|
| | | | | |
| | **Time availability** | Does the operator feel time pressure? | Floor manager makes sure time pressure does not get to the work floor. | **Sufficie nt** |
| | **Sensorial** | Eyes and sometimes tactile senses needed to detect Flatness, dirt, length, kinks, but does the operator use ears, nose and taste? | Indeed, eyes and tactile senses. | **2** |
| | **Cognitive requisite** | Does the operator uses his own judgement to overcome variability? Detects wrong length for example and cuts it off. | Definitely. Constantly judging if the material is sufficient. Or checking the label and serial number to determine the sequence and checking the measurements between the dotted lines. | **Yes** |
| | **Physical demand** | Very detailed and product is very sensitive, cannot touch anything sharp. | Additionally recently, an employee mentioned that they found the task too demanding. | **Yes** |

## G. Confidential scale

All confidential numbers in this report are scaled by a factor Y to ensure data confidentiality.