Human vs. machine. Navigating the automation trade-offs

A methodology for evaluating automation level trade-offs in production line design

SEN232A: Master Thesis

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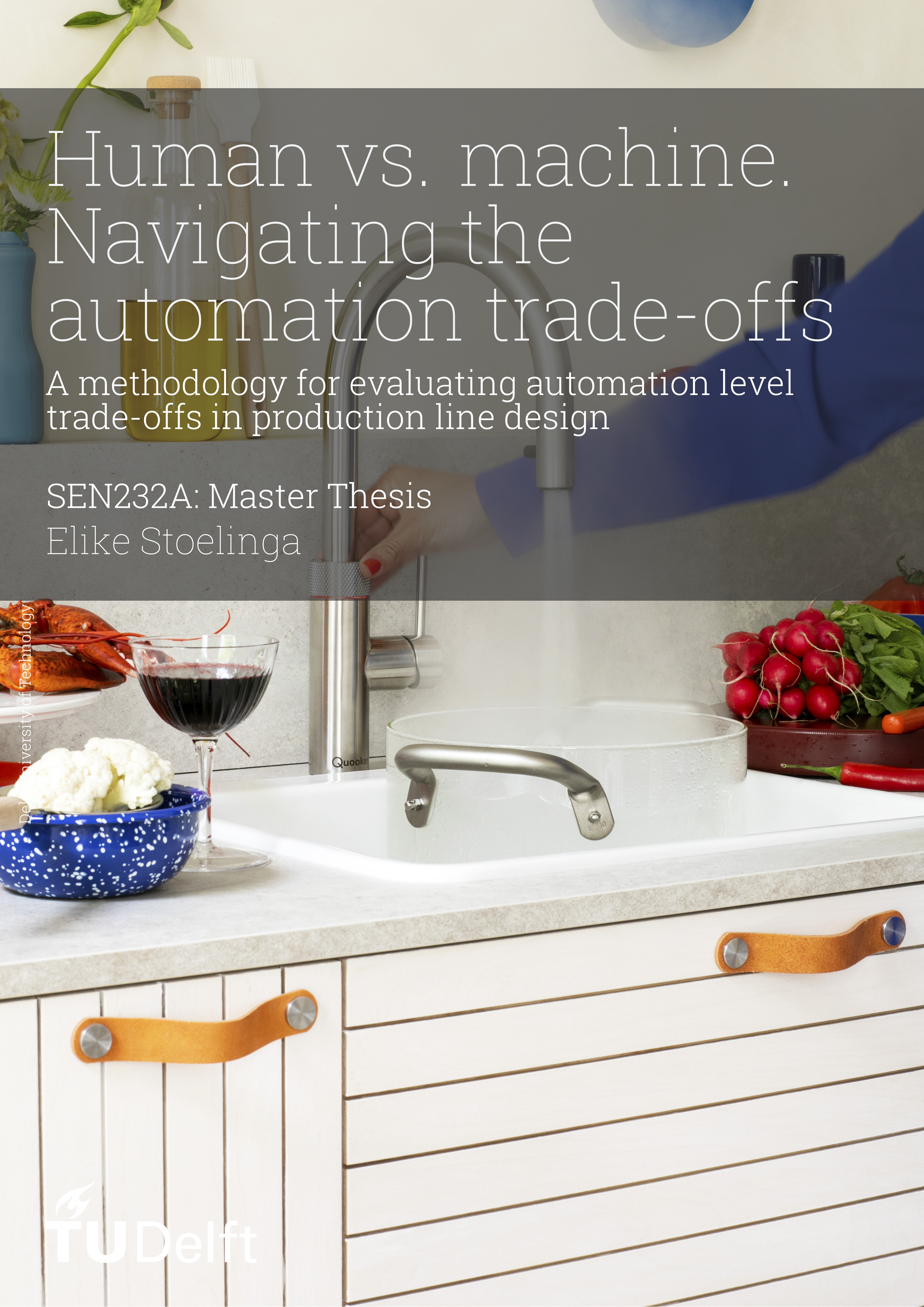

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by

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Preface

This report marks the end of my journey as a student. After nearly six years of studying at TU Delft, I look back with gratitude and pride at a period filled with learning, growth, and a lot of new friends.

The process of writing this thesis has truly been a journey. My graduation internship at Quooker played a significant role in shaping this experience. Much of my time was devoted to thoroughly understanding Quooker's production line, which served as the test case for my research. As a systems engineer within the mechanical engineering team, this was sometimes challenging. However, being able to walk over to the test line and see things fall into place was both fun and enlightening.

Before this project, my knowledge of the manufacturing industry was quite limited. Through this thesis, I have gained valuable insights that have greatly expanded my perspective. The biggest challenge of this thesis was the development of the dynamic model that required many late nights and weekends, but I am proud of what I have accomplished overall. In the end, I designed an automation evaluation methodology, applied it comprehensively to the Quooker test case, and incorporated a wide range of elements. Additionally, I conducted three feedback sessions where I presented my methodology to manufacturing experts. As a newcomer to the industry, these discussions were both challenging and inspiring, and I found the feedback to be incredibly positive and constructive.

I would like to express my sincere gratitude to Alexander Verbraeck for his in depth feedback and constant availability. Your expertise and guidance consistently pushed me to achieve my best. I also want to thank Stefano Fazi for his valuable feedback. Finally, a special thanks to Xander Boomars, my supervisor at Quooker, who went above and beyond to help me, whether it was brainstorming solutions to thesis challenges or taking a break for a game of table tennis when I needed it most.

Elike Stoelinga
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Summary

In today's manufacturing sector, companies are confronted with rising global competition from low-cost countries and have to deal with ongoing labor shortages. These challenges create a growing necessity to achieve the highest possible efficiency in production to stay ahead of competition. Automation has emerged as a key strategy for manufacturing companies seeking to maintain a competitive edge. However, making automation decisions is complex and involves weighing the strengths of human operators, such as their flexibility and problem-solving abilities, against the benefits provided by machines, including consistency and strength. A literature review has revealed that there is currently no readily available method that enables companies to assess the trade-offs between various factors that result from different automation options in a way that integrates both quantitative and qualitative considerations across multiple key-factors. This knowledge gap leads to the following main research question: *What is a good methodology for evaluating trade-offs between key-factors of different automation levels in early-stage production line design?*

To address this question, the research applied a design science approach, developing and iteratively refining a methodology through three structured feedback sessions and practical application in a real-world test case at Quooker, a company designing a new production line. The methodology centers on a framework of five key-factors: quality, work environment, flexibility, cost, and production performance. These factors, grounded in literature and industry conventions, ensure the methodology evaluates trade-offs comprehensively rather than focusing solely on single factors.

The designed automation evaluation methodology consists of six structured steps:

0. **Preparation:** Define context, requirements, and constraints.
1. **Scenario creation:** Identify automation options and create low, medium, and high automation scenarios.
2. **Conceptualization:** Visualize each scenario with models and layout maps.
3. **Dynamic modeling:** Simulate scenarios to analyze performance and bottlenecks.
4. **Comparison:** Compare scenarios on production performance, cost, quality, work environment, and flexibility.
5. **Synthesis:** Summarize insights to clarify trade-offs and guide decisions.

Analysis and feedback identified three key differentiators that set this methodology apart from existing approaches:

- Integrates multiple modeling types for a comprehensive look at automation.
- Structures trade-offs with five key industry factors for practical, well-rounded evaluation.
- Involves stakeholders early with clear visuals and structured discussions to support informed choices.

The application of the methodology at Quooker confirmed its ability to structure early-stage design discussions, support comprehensive trade-off analysis, and generate valuable insights. Experts praised the method's holistic nature and the explicit consideration of multiple key-factors, which allowed moving beyond narrow focuses like cost or throughput alone. The methodology's structured process and visualization of scenarios enabled clearer discussions and broadened perspectives among stakeholders.

However, limitations were also identified. The methodology relies on sufficient and reliable data for building dynamic models, limited data increases the need for assumptions and can reduce accuracy. Dependence on expert input can introduce bias if a narrow range of perspectives is included. Additionally, developing high-quality dynamic models can be time consuming, and factors beyond the defined key-factors, such as maintenance, may fall outside the methodology's current scope.

Several factors support the generalizability of the developed methodology. Built on a design science approach that focuses on creating solutions for classes of problems rather than individual cases, the methodology inherently encourages abstraction and identification of underlying principles. Input from multiple industry experts during the feedback sessions provided diverse perspectives, significantly enhancing the method's broader applicability. Each step of the methodology enables customization, making it adaptable to different manufacturing contexts. Moreover, the methodology is based on standardized metrics and terminology, including five key-factors widely used to assess automation levels in production line design. This foundation ensures the methodology aligns with industry conventions, making it recognizable and acceptable across different companies.

For practical use, it is recommended to first gain a thorough understanding of the production process, as foundational knowledge enables a strong start. Engaging diverse experts enriches analysis and reduces bias, while organizing workshops helps gather input and stimulate discussion for more balanced outcomes. Documenting insights and decisions immediately maintains clarity, preserves knowledge, and supports transparency for later stages. When developing dynamic models, aiming for professional quality and involving experienced specialists can save time and avoid pitfalls.

To address identified limitations, future research should develop simplified versions of the methodology that provide comparable insights with less modeling effort, while evaluating the trade-off between speed and result quality. Testing the methodology in additional companies is needed to assess generalizability and refine the approach based on broader practical experiences. Including maintenance as an explicit key factor could further increase practical relevance. Finally, research should focus on creating clear guidance for translating insights from the methodology into actionable automation designs, bridging the gap between analysis and implementation.

In conclusion, the developed methodology offers a robust, systematic, and adaptable framework for early assessment of automation scenarios. By structuring discussions, visualizing trade-offs, and integrating quantitative and qualitative insights across five key-factors, it supports informed, transparent, and balanced automation decisions, addressing a critical knowledge gap in manufacturing.

Contents

1
Introduction

In this chapter, the research will be introduced. It begins with the introduction of the problem and the research objectives in Section 1.1. Following this, the scientific relevance is outlined in the literature review presented in Section 1.2, which identifies the knowledge gap and leads to the main research question discussed in Section 1.3. The research question informs the research approach, which is elaborated on in Section 1.5. Finally, Section 1.4 addresses the sub-questions that arise from the main research question and explains how they will be answered.

1.1. Problem introduction and research objective

In today's rapidly changing technological landscape, established tech giants are facing significant challenges in their attempts to maintain a competitive edge globally. This is the result of rising global competition and the challenges posed by outsourcing to low-cost countries [1].

To stay ahead of the competition, companies can employ various strategies. Of which one effective approach is to maintain low product prices through innovation and cost reduction [2]. Where a significant portion of the costs associated with complex products, such as technology items, lies in manufacturing.

A widely recognized approach for increasing productivity would be to apply automated manufacturing systems, thereby enhancing a company's competitiveness [1]. Automation today does much more than increase productivity; it is actively reshaping the manufacturing industry by improving efficiency, safety, and product quality while opening up new possibilities for innovation and growth. This increased capability of machines, combined with rising wages and labor shortages [3] has launched a new era of automation in manufacturing.

Automation and human workers in manufacturing

The trade-off between automation and human operators is a critical consideration for manufacturers. On one hand, automation can dramatically increase efficiency and reduce human error [4]. On the other hand, human operators bring flexibility, problem-solving skills and the ability to handle complex or unexpected situations that machines may struggle with [4]. An overview of the relative strengths of humans and the relative strengths of machines is given by Groover [4] that is shown in Table 1.1.

As manufacturers navigate this complex landscape, they must carefully weigh the benefits and drawbacks of automation against the value of human expertise and intervention. The challenge lies in finding the optimal mix of automated processes and human involvement that maximizes productivity, quality, and cost-effectiveness.

Automation in manufacturing typically takes over repetitive tasks, allowing human operators to focus on more creative and intellectual work [5]. As human operators are assigned more knowledgeable tasks to collaborate effectively with the machines. While this approach creates more opportunities, it also presents new challenges for automation in manufacturing.

Table 1.1: The strengths of the humans vs. machines from Groover [4]

Relative Strengths of Humans	Relative Strength of Machines
Sense unexpected stimuli	Perform repetitive tasks consistently
Develop new solutions to problems	Store large amount of data
Cope with abstract problems	Retrieve data from memory reliably
Adapt to change	Perform multiple tasks at the same time
Generalize from observation	Apply high forces and power
Learn from experience	Perform simple computation quickly
Make difficult decisions based on incomplete data	Make routine decisions quickly

The new dynamic between automation and human workers introduces a new approach to task allocation. Qualified operators and automated machines can complement each other when sharing the same tasks, creating a synergy between human and technological components [6]. This concept introduces a continuum of different degrees of task sharing between humans and technology, divided into different levels of automation (LoA) [7].

Level of automation in the design of a manufacturing system
Manufacturing costs can be significantly influenced during the early stages of production line design [8]. Studies have shown that up to 70% of a product's life cycle costs are determined during the initial design phase [9]. Therefore, this stage is crucial. To effectively utilize the strengths of both automation and human operators within a manufacturing system, it is important to consider these elements in the design process. The early phase of manufacturing design focuses on system design and automation decisions. This period involves anticipating the design of the system, which is not yet fully developed or finalized. During this phase, preliminary studies are conducted to assess the level of automation for the manufacturing process, taking into account various criteria [10].

When deciding on the level of automation, it's essential to consider a variety of trade-offs that can significantly impact the manufacturing process. One major consideration is the flexibility of human operators compared to the consistent quality provided by machines. While human workers can adapt to changing conditions, machines ensure uniformity in production quality. One example is that higher levels of automation often come with increased investment costs. However, the variable costs tend to be lower due to reduced labor costs, which can be financially beneficial in the long term. Additionally, certain quality checks are better performed by human operators because they rely on human senses, although machines can execute these checks more quickly. These examples illustrate potential trade-offs among different factors, including cost considerations. Ultimately, the level of automation chosen must align with the broader manufacturing strategy of the company, ensuring that it supports long-term goals and adapts to changing market needs [11].

These are just a few examples of the trade-offs involved; in reality, there are many more considerations that companies must take into account when deciding on the optimal level of automation. Quooker, a manufacturing company known for its innovative tap system that provides instant boiling water, is currently facing these trade-offs in terms of automation. As Quooker develops a new product design that differs from their existing products, they need to create a new production line. They currently have a proof-of-concept line in place to demonstrate how to manufacture the product, and they are now moving into the stage of scaling this design up to an industrial level. This stage involves making key decisions about automation in the new production line. As a company dealing with these challenges, Quooker serves as an important test case for this research.

Research objective
In the evolving landscape of manufacturing, where automation is becoming increasingly important, companies must consider various factors when designing a production line and determining the appropriate level of automation. The objective of this research is to explore how to incorporate these trade-offs of automation into the early stage production line design.

By examining these trade-offs in depth, this research aims to design a comprehensive methodology that can guide manufacturing companies in creating insights and assessing the effect of level of automation the the production line design. Ultimately, the goal is to help companies strike the right balance when deciding on the level of automation in their production processes.

1.2. Literature review on methods for evaluating the LoA

Determining the level of automation in the design of a manufacturing system requires an analysis of the performance associated with different levels of automation. The literature indicates that there are two primary approaches for making strategic decisions regarding automation levels in manufacturing systems: decision support methods and modeling approaches. Decision support methods assist decision-making by using structured frameworks and incorporating human judgment, taking into account various factors beyond just technical considerations. In contrast, modeling approaches rely on quantitative analysis and mathematical models to optimize specific parameters. This literature review examines these two approaches for analyzing the level of automation in manufacturing design, as they form the foundation of existing research in this field. Additionally the literature review also looks at more general methods that are used in production line that are uses to asses trade-offs between different factors in production line design, but do not specially focus on the effect of the level of automation. An overview of the literature can be found in Appendix A.

Decision support methods

The first individual to develop a decision support method centered around levels of automation was Kapp in 1999 [12]. He introduced the USA (Understand, Simplify, Automate) principle, emphasizing that many companies tend to jump straight into automation without first taking the time to understand and simplify their processes. Kapp argued that these initial steps are crucial, as they should serve as the foundation for effective automation. While this approach provides a general framework, it remains quite broad and does not specify detailed steps or offer recommendations for determining the optimal level of automation. In 2000, Parasuraman, Sheridan, and Wickens [13] followed with a decision support method for levels of automation that involves a flowchart consisting of iterative steps and including two main criteria. The first criterion focuses on the consequences of specific types and levels of automation for human performance. The second evaluation criterion encompasses factors such as automation reliability and the costs associated with decision/action consequences, among others. However, these criteria are not quantifiable and do not lead to an intregrated automation scenario.

Konold and Reger [14] have developed a method that considers cycle time, production volume, and product lifetime to determine a single level of automation for an entire production line. However, this method has a downside: it focuses solely on production performance, and does not take into account other factors. On the other hand, Boothroyd's [15] method incorporates cost into the equation by calculating the unit cost of the product. He estimates the cycle time for each station, the cost of each machine or robot, labor costs, the efficiency rate, and quality control costs. While this quantitative approach leads to one optimal automation configuration, it has two main downsides. First, it simplifies the cost of machines by not differentiating between different types, even though machine costs can vary significantly and greatly impact the calculations. Second, cost is not the only indicator for comparing levels of automation. Factors such as quality and flexibility are also important but are not addressed in this method.

A method that completely goes away from cost is a method developed by Almannai, Greenough and Kay [16] they have developed a decision support tool was that combines Quality Function Deployment (QFD) and Failure Mode and Effect Analysis (FMEA). The methodology involves three steps: first, identifying criteria related to company objectives using QFD; second, identifying automation alternatives through a second multi criteria analysis; and finally, assessing the solution with FMEA to identify associated risks and failures. While the method aligns with company goals and uses evaluation criteria for optimal automation choices, it lacks a list of criteria and clarification on defining automation alternatives.

The most discussed decision support methodology in literature is the DYNAMO method. The DYNAMO method, developed by Lindström and Winroth [11], is a decision support approach for aligning manufacturing strategy with automation levels. It consists of eight steps that help manufacturers analyze the production flow, the constraints of each station, and the operations performed. Fasth and Stahre [17] expanded this method into DYNAMO++, which enhances data analysis and incorporates a company's specific "Triggers for Change." This ensures that assessments of the level of automation are aligned with company objectives, such as increasing flexibility or reducing time parameters. The analysis of all this data enables to identify the minimum and maximum possible levels of automation for each operation. These minimum and maximum levels can then be assessed based on a set of criteria aligned with the company's strategy. Although this approach has the advantage of taking into account various factors, such as system constraints and the company's strategy, it does not provide decision support for determining the suiting level of automation.

The various decision support methods used to determine the level of automation primarily focus on specific aspects such as cost, company strategy, and reliability. However, these methods are often not quantified and do not lead to a definitive optimal solution for automation. A more data driven approach can be found in modeling, which helps to directly compare different automation levels with quantitative outcomes.

Modeling to determine LoA

While decision support methods offer flexibility and broader perspectives, modeling approaches provide standardized, data-driven results for reviewing automation levels. The most found type of models for determining an optimal automation level are cost models. Cost modeling for determining an optimal level of automation involves evaluating the financial implications of different automation levels, considering factors like initial investment, maintenance, labor, energy consumption, and potential cost savings from increased efficiency and reduced errors. One of the earlier and well-referenced cost estimation models is Son's model from 1991 [18]. This model is considered advanced due to its thorough consideration of both tangible costs, which are relatively well-structured (like labor and materials), and intangible costs, which are relatively ill-structured (such as quality and flexibility). It calculates costs per manufacturing job, making it useful for automation analysis. The model's strengths lie in its comprehensive approach to cost elements. On the downside, it lacks detailed guidance on how to compute many of the cost components and does not incorporate time values or product design factors. Salmi et al. [10] have proposed an outline for an integrated cost estimation approach that leverages the strengths of Son's method [18] by incorporating both tangible and intangible cost drivers and combing this with the cost estimation approach developed by Boothroyd et al. [19], which emphasizes the significance of product design complexity and time estimation based on automation levels. The cost modeling framework presented by Salmi et al. [10] includes these factors as inputs, categorized into three groups: product design, time standards, and cost drivers. This structured approach leads to a final cost per product. By combining the strengths of multiple models, it offers a more comprehensive and accurate cost estimation. However, this complexity can make it challenging to gather the necessary cost data in practice.

When considering the cost to determine the optimal level of automation, it is important to understand that this approach oversimplifies the operational aspects of a production line. While it provides a cost-based estimate for the cycle times of each step, it does not account for operational efficiency metrics, such as overall equipment effectiveness. This aspect is crucial for determining the appropriate level of automation. If a cost-efficient level of automation is selected but the system is not operating efficiently, it is likely that the project will not meet the estimated costs. A more holistic approach to determining the optimal level of automation is proposed by Gorlach and Wessel [20], who consider factors such as cost, productivity, quality, and flexibility. They utilize matrices to compare different production methods and identify the best automation strategy. While this comprehensive approach accounts for various aspects beyond just cost, it does not explicitly address operational efficiency. Simulation can bridge this gap.

An other type of modeling is simulation. Johanssin et al. [21] propose using discrete event simulation (DES) as a tool to study the impact of different levels of automation on the design of manufacturing systems. They suggest employing the SIMTER simulation tool for this purpose. SIMTER is designed to analyze how various automation levels affect manufacturing systems, taking into account factors such as system performance, ergonomics, and environmental impact. While SIMTER provides valuable insights regarding the feasibility of different automation levels, it is still under development and is not as advanced as other DES simulation software. Additionally, it lacks optimization options found in more established DES tools. Furthermore, the case presented by Johanssin et al. is based on a ”toy case” scenario, which may be unrealistic or infeasible in real-world applications. They acknowledge that a case study is necessary to demonstrate the potential of using DES with automation levels as a design parameter.

Production line design
The two previous paragraphs discussed two approaches to determine the level of automation in a production line and concluded that there is no specific or general method for this. Ultimately, determining the level of automation involves a method that investigates trade-offs in the design of a production line. There are general methods for weighing decisions in production line design, which this paragraph will discuss. These general approaches have different focus points in their methodologies.

Khan and Day [22] have developed a knowledge based design methodology with two stages: knowledge acquisition and an analytical model. The knowledge stage uses if-then-else statements, while the analytical model consists of cycle time analysis, parallel line options, line balancing, and the feasibility of workstation combination. Yoshimura et al. [23] have created a collaborative rapid analysis method for use at the conceptual stage. They argue that a conceptual stage is necessary in the design process, which should be based on rapid analysis and incrementally improved until it is ready for detailed design evaluation through simulation. Kim and Nof [24] focus on the human factors of operators and have developed a methodology that enables the creation of quantitative models to analyze the relationships between the working environment, direct workers, and their subsequent performance. Hsieh [25] has provided a hybrid analytic and simulation model. The paper introduces a class of hybrid models where simulation outputs serve as inputs for an independent analytic model. This approach is particularly useful when relationships between parameters and performance measures are poorly understood, making it difficult to develop purely analytic models. Lastly, the most holistic methodology is presented in the book ”Assembly Line Design” by Chow [26], which covers all relevant aspects of assembly line design, focusing on practical cases. This book discusses fundamental concepts of assembly line design, along with subjects such as process design, line simulation, and design analysis. It is a comprehensive resource specifically dedicated to assembly lines. The studies discussed provide general methods for decision-making in the design of a production line, but they have not yet specifically focused on choosing the appropriate level of automation in early stage production line design.

1.3. Knowledge gap and research question

In the literature, there is a greater focus on decision support methods and modeling approaches to help on deciding the level of automation in production line design. However, the analysis reveals that one downside of these decision support methodologies is that they are often not quantifiable and do not lead to final well-balanced automation solutions. In contrast, modeling provides this option. The primary type of modeling used is cost modeling, which tends to oversimplify the operational aspects of a production line. While it offers a cost-based estimate for the cycle times of each step, it fails to account for other key-factors such as the operational aspect.

Furthermore, while there are general methods for production line design, these methodologies do not focus specifically on choosing the appropriate level of automation. This leaves a gap in providing a concrete way to determine the level of automation. Essentially, there is no readily available, off-the-shelf method that a company can implement to effectively consider the trade-offs of different levels of automation in their production line design.

As previously stated, this research explores the trade-offs manufacturing companies face when assessing automation levels in early stage production line design. This objective led to a literature review, which revealed that there are decision-making support methodologies with specific scopes and modeling approaches that focus on the cost or operational effectiveness associated with different levels of automation. However, the literature review also identified a knowledge gap: there is currently no structured methodology that combines the qualitative insights from decision support models with the quantitative insights from modeling approaches to comprehensively analyze trade-offs among different factors in early-stage production line design. This provides the following main research question:

What is a good methodology for evaluating trade-offs between key-factors of different automation levels in early stage production line design?

1.4. Sub-questions

The main research question guides the formulation of sub-questions, the research methods for each sub-question, as well as the necessary data and analysis tools needed to address them. The main research question led to the formulation of the following sub-questions:

1. What are the key-factors to consider when evaluating the trade-offs between different automation levels in early stage production line design?

The objective of the first sub-question is to identify the factors influencing the trade-off between automation levels and human operators in a manufacturing system. This trade-off is the main characteristic of the research, and this chapter will provide a foundation for the rest of the study.

To address this sub-question, a dual approach will be employed, which combines a literature review with theory testing. This process will involve applying the key-factors identified in the literature to the Quooker case, allowing for the testing of the practical applicability of these factors. Additionally, feedback on the key-factors will be gathered from industry experts.

The literature search will focus on academic perspectives, while the test case will provide insights specific to the industry. It is important to note that the literature search may not be exhaustive, as there is no guarantee that all relevant literature on the topic has been reviewed [27]. Additionally, the test case from Quooker may provide insights that relate specifically to their manufacturing system, which might not be applicable to other contexts. This combined approach of using literature and an interview helps to mitigate the limitations of each method: while the literature search may overlook some elements, the information provided be Quooker could be too narrowly focused on their particular practices [28]. Together, these methods will create a more comprehensive understanding of the trade-offs. For the literature search, Scopus will be utilized, as it is one of the largest multidisciplinary databases of peer-reviewed scientific articles [29]. Results from Scopus can be directly imported into the reference management tool, Mendeley, allowing for organized and labeled sources for data analysis.

2. What are the key steps in a methodology to provide insights of the trade-offs between key factors of different levels of automation in early stage production line design?

The goal of the second sub-question is to create a methodology for assessing the trade-offs of the key-factors identified in sub-question 1, related to various levels of automation in production line design. The second sub-question is about the design of a methodology that incorporates these key-factors to asses tradeoffs in production line design. This process consists of multiple iterations of the assessment methodology. Therefore, the methodology used for this sub-question will follow an iterative design process. The iterative process will involve three feedback sessions on the methodology, each viewed through a different lens. One session will focus on insights from the manufacturing industry, another will assess the practicality of the methodology based on test cases from Quooker, and the third will offer an academic perspective.

This iterative approach allows for ongoing refinement and enhances both the relevance and rigor of the methodology. It aligns well with the design science approach and ensures that the final design is well-suited to the specific needs of the production line. As identified in the knowledge gap, the methodology will focus on the combination of the qualitative nature of the decision methodologies in combination with the quantitative approaches of the modeling methodologies along with taking into account multiple key-factors.

One advantage of starting with a draft design of the methodology and improving it through feedback sessions is that this approach allows for adaptability as new insights emerge during the evaluation process. This adaptability is crucial when designing a methodology that can be used in practice and generalized. However, a limitation of iterative processes is that they often require significant resources for multiple rounds of prototyping, testing, and refinement. Due to the time constraints of this thesis, not every aspect will be included in the final design, which may lead to some important considerations in the designed methodology being overlooked.

The data required for the test case includes detailed information regarding Quooker's manufacturing process. A substantial amount of data is necessary to asses the the different levels of automation, including details about events, time intervals for each step, cycle times, queue lengths, and more.

During the thesis period, test runs will be conducted on the proof-of-concept line, which will provide most of the necessary data. However, there is a possibility that not all data will be available. For any unavailable data, assumptions may be made based on information from other manufacturing systems.

3. What is the effectiveness of the designed methodology in a practical context to assess trade- offs between automation levels in early stage production line design?

Sub-question two has provided a methodology to assess the effect of different automation levels in production design. The goal of the third sub-question is to assess the methodology developed, as evaluating the final designed automation evaluation methodology will determine what a ”good” methodology is, as this is a part of the main research question. This can be accomplished by applying the methodology to a test case of Quooker to gain industry insights and organizing feedback sessions with different lenses.

The effectiveness of the methodology will be evaluated through a combination of practical application and structured feedback sessions. Using the Quooker test case as a real-world example will provide validation, showing how the methodology performs in an actual production line design scenario. This ensures the methodology is not just theoretical but is grounded in practical challenges and constraints. However, relying on a single test case may introduce bias, as the results could be specific to Quooker's context. To address this, the methodology will also be reviewed in three separate feedback sessions, each offering a different perspective. One session will involve an industry company to gather industry feedback, another will be held with Quooker to obtain practical feedback, and a third session will be conducted with an academic group to ensure scientific rigor.

During these feedback sessions, the methodology will be discussed step-by-step, allowing participants to provide targeted feedback for each phase. This approach is designed to capture a wide range of perspectives and insights. However, it is important to recognize that each group brings its own lens, which may introduce certain biases into the evaluation. Expert feedback, while valuable, always carries some subjectivity. To encourage open and honest input, all experts will remain anonymous and will have the opportunity to review how their feedback is represented in the public thesis.

By combining the test case with feedback from diverse groups, the methodology will be refined and its applicability and limitations will be better understood. This approach aims to ensure that the methodology is both practical and scientifically sound, while also acknowledging the influence of different perspectives and the potential for bias.

1.5. Research approach

The formulation of the sub-questions leads to the research approach. This research focuses on developing a methodology to asses the trade-offs between different levels of automation in the design of a production line. To achieve this, the study will propose a unique methodology. The research approach that will be used for this is design science, which is a scientific method centered on the systematic creation and evaluation of artifacts to solve problems and enhance human performance [30]. This paradigm bridges the gap between theory and practice, with the aim of generating prescriptive knowledge in various fields, particularly in information science and engineering.

At the core of design science is the creation of an artifact [31], which may take the form of constructs, models, methods, or instantiations. The artifact is designed with a problem-solving emphasis, addressing significant business challenges through technology based solutions. A key feature of design science is the iterative process, which follows a build and evaluate loop, resulting in the repeated creation, testing, and refinement of artifacts.

A widely accepted methodology for design science research is from Pfeffers et al. [30], who introduced the Design Science Research Methodology (DSRM). This methodology consists of six steps: 1. Problem Identification; 2. Definition of Objectives for a Solution; 3. Design and Development; 4. Demonstration; 5. Evaluation; 6. Communication. The DSRM can serve as a foundation for creating the methodology to determine the level of automation. These steps are in line with the methods used per sub-questions.

One advantage of design science method is its relevance, as it directly addresses practical, real-world challenges faced by organizations and society, leading to solutions that are immediately applicable and valuable [32]. This quality aligns well with the objective of creating a methodology for manufacturing companies. Another advantage is rigor: design science research emphasizes a thorough process of design, development, and evaluation, ensuring that the resulting artifacts are effective, efficient, and of high quality [32]. This rigor can be applied to the Quooker case by allowing for multiple iterations of the methodology and obtaining feedback from Quooker and other industry experts on these various versions.

However, a limitation of this approach is that a designed methodology is not always generalizable. Solutions developed for a specific context may not be directly transferable to other situations without modification [33]. This may also apply to this research, which will use a single test study to test the designed methodology. Awareness of the company-specific assumptions made during the research can help address this limitation. Furthermore, since Quooker is not significantly different from other manufacturing companies, this similarity can aid in the generalization of the findings.

2
Trade-offs between key-factors in automation

When determining the level of automation in production line design, various trade-offs must be considered. These trade-offs are influenced by key-factors. This chapter provides a literature overview of these key-factors in Section 2.1. Then, in Section 2.2, the definition of the levels of automation and the differences between them are provided.

2.1. Key-factors

Deciding on the level of automation ultimately involves a trade-off analysis between the advantages and disadvantages of that level of automation. For instance, machines can produce goods more continuously and produce at higher speed, while human operators are more adaptable to changing conditions, such as variations in materials. This example highlights two important key-factors: quality and flexibility. Overall, this research focuses on five key-factors: quality, work environment, flexibility, cost and production performance. These five main key-factors are derived from two foundational research studies in this field. The first study, conducted by Neely et al. [34], is a literature review that examines the key dimensions of manufacturing performance. The second study, by Granell et al. [35], surveyed production managers to identify the factors that should inform decisions about automation. This chapter will further explore how these key-factors influence the evaluation of the trade-off between automation and human operators in manufacturing.

2.1.1. Quality

According to research by Granell et al. [35], production managers consider quality to be the primary factor influencing decisions about automation. According to Crosby, quality can be defined as conformance to quality requirements [36]. An important aspect of quality is quality checks. Quality checks operate on a binary concept, as an quality check can either be passed or not. This binary nature of quality assessments ensures that every product is evaluated against clearly defined and measurable standards. Crosby argues that the requirements must be articulated in measurable and clear terms to establish a definition of quality. ”Quality is either present or absent.” A product either meets the requirements or it does not, leading to straightforward outcomes: it either requires rework, is defective, or is returned by customers, or none of these issues occur. Quality can be separated into two different aspects: the quality of the design product and the quality of the production process [37]. The quality aspect in the production of a product is whether it adheres to the design standards. It either meets the design standards or does not.

Because both aspects stem from different factors, there are distinct metrics to assess them. For the production process, it is essential to differentiate between units that require rework and defective units. Rework refers to products that need modifications in a specific part of the production process to meet predefined standards [38]. To assess the performance of the rework, a rework ratio can be calculated;

see Equation 2.1. In this equation, the number of rework activities is used, as a product might have multiple rework activities. In contrast, defective units are those that do not meet these standards and cannot be brought up to standard through rework; they are not used further. The metric for this is the defects compared to the total produced units [38], see Equation 2.2. This evaluation can be carried out for the entire production process or for each individual step in production.

$$\text{Rework ratio} = \frac{\text{number of rework activities}}{\text{total number of units produced}} \tag{2.1}$$

$$\text{Defect ratio} = \frac{\text{number of defect units}}{\text{total number of units produced}} \tag{2.2}$$

If the final product meets production standards, it becomes available for sale to customers. At this stage, the second aspect of quality comes into play: product quality, which reflects the product's performance in the field. This can be assessed by comparing the number of returned units to the total number of units sold [38], as shown in Equation 2.3. The units sold refer to the items that have left the manufacturing plant. Whether they are officially sold later by an intermediary business or are directly sold to the final customer, they are all considered as units sold. All the quality metrics give a score between 0 and 1. The closer to 0, the better.

$$\text{Return ratio} = \frac{\text{returned units}}{\text{total number of units sold}} \tag{2.3}$$

To achieve high quality manufacturing, two main aspects must be considered: 1) design a manufacturing system that ensures products are consistently produced to high-quality standards. 2) implement rigorous inspection processes to ensure that only high-quality products are delivered to customers [4].

The quality factor in the trade-off of automation levels has two main aspects. First, automated systems offer high precision and consistency in manufacturing processes. Machines are very accurate, while humans are more prone to mistakes due to fatigue and subjective judgment [39]. The second aspect of quality in this trade-off is quality control. Human operators excel at complex and subjective quality control tasks. They can detect subtle defects, assess product aesthetics, and make critical judgments that machines may struggle with on their own. This underscores the need for a lower level of automation in quality checks [39]. These two aspects are generally observed in most cases, but may not always hold true.

The ratio of rework, defects, and returns that indicate quality performance is difficult to predict during the design phase of a production line. This is because the necessary data is based on measurements taken from an operational process. While it is possible to create a test setup to provide estimates, this is not always feasible, as it requires actual processes, tools, and machines, which entails significant investment. Therefore, experts play a crucial role in evaluating different automation options based on the design. They can leverage their expertise to estimate the impact on quality at various levels of automation.

2.1.2. Work environment

The second most important factor influencing the decision to automate, according to production managers, is the work environment [35]. Work environment can be connected to the safety of workers and their job satisfaction.

Creating a safe work environment in manufacturing is crucial for protecting employees from injuries, illnesses, and hazards inherent to the manufacturing process. One key motivation for automating manufacturing operations is to remove workers from hazardous conditions [4]. Automated systems often perform dangerous tasks that would otherwise require manual labor. However, workers are still needed to service equipment regularly, making it essential for automated systems to operate safely when workers are present. Safety involves minimizing potential hazards and their impact to reduce risks. In the manufacturing industry, using ISO standards to assess these risks is considered the industry norm. According to EN-ISO 12100 [40] (Safety of machinery — General principles for design — Risk assessment and risk reduction), safety risk is defined as a combination of the probability of damage occurring and the severity of that damage. ISO/TR 14121-2 (Safety of machinery — Risk assessment) [41] provides the guidelines for the levels of severity, these guidelines for the levels of severity are provided in Appendix B.1.

Probability levels are influenced by the frequency of task execution. Consequently, the categories of probability levels are context-dependent [42], meaning these levels can be adjusted based on the specific requirements of a manufacturing system. The varying levels of severity and probability categorize risks as low, medium, or high as shown in Table 2.1. The levels of low, medium, and high are bolded, while negligible is not. This is because negligible indicates a risk so minimal that it typically requires no further action.

Table 2.1: Risk estimation matrix adjusted from ISO/TR 14121-2 [41]

Probability of occurrence of harm	**Severity of harm**			
	Catastrophic	Serious	Moderate	Minor
Very likely	**High**	**High**	**High**	**Medium**
Likely	**High**	**High**	**Medium**	**Low**
Unlikely	**Medium**	**Medium**	**Low**	Negligible
Remote	**Low**	**Low**	Negligible	Negligible

The safety standards mentioned above are current norms, but safety regulations change over time. Therefore, it is important to incorporate future regulations as well. An example of this is that for EU manufacturing companies, a new guideline will come into effect in 2027 with a new Machinery Directive [43]. The biggest changes will include requirements for artificial intelligence, the Internet of Things, and cyber security. The regulation now addresses these new technologies to ensure they contribute to machine safety. Specific requirements have been added to protect machine safety from cyber attacks. This new regulation is closely related to the level of automation in a manufacturing system. When designing a production line, it is crucial to consider the development of safety requirements that will be effective in the future. Companies are taking this into account through the ALARP principle (As Low As Reasonably Practicable), which aims to reduce risks to a level that is reasonable, recognizing that further risk reduction may not be easily achievable [44]. Therefore, the safety assessment should also consider the new Machinery Directive.

The risk assessment mentioned above focuses on hazardous situations, while another important aspect of safety is ergonomics. It is important to incorporate ergonomics in the design of workplaces, as non-ergonomic environments commonly lead to work related musculoskeletal disorders [45], resulting from prolonged wear and tear on tendons, muscles, and nerve tissue. As discussed in ISO/TR 14121-2,[41] "The proposed risk graph is not very appropriate for estimating risks related to certain health hazards, such as noise or ergonomics." Therefore, a different standard is used to determine ergonomics levels. The NEN-EN 614-1+A1 (Safety of machinery - Ergonomic design principles - Part 1: Terminology and general principles) [46] provides guidelines that should be taken into account when designing an ergonomic workplace, this can be divided into two categories: operators characteristics and physical work environment. Operators characteristics consist of: 1) body dimensions 2) posture 3) body movements 4) physical strength 5) mental abilities. Physical work environment consist of: 1) noise 2) vibration 3) thermal emissions 4) illumination.

The adherence to these dimensions of ergonomics leads to three distinct zones. The green zone represents conditions that are good and acceptable for frequent and long duration tasks. The yellow zone indicates that ergonomic principles are met, but only to a degree that is suitable for temporary or short term tasks. The red zone signifies a failure to meet ergonomic principles and is not acceptable for any type of task. The specification of the zones can be found in Appendix B.2.

In addition to the ergonomic design principles and conducting a risk analysis, there are guidelines to ensure a safe work environment for workers. Local regulations must be adhered to, including the Work Conditions Act and Occupational Health and Safety regulations.

The second aspect of the factor work environment is job satisfaction. A common definition of job satisfaction is “a pleasurable or positive emotional state resulting from the appraisal of one’s job or job experiences” [47]. There are two main reasons to consider job satisfaction. First, individuals spend a significant portion of their life at work, which greatly influences their overall well-being [48]. Second, a worker’s job satisfaction is directly related to their motivation and effort in the workplace [49].

A major instrument for measuring job satisfaction is the Job Diagnostic Survey developed by Hackman and Oldham. This survey assesses job satisfaction across seven job characteristics, each rated on a 7-point scale ranging from ”very little” to ”very much.”

1. *Skill variety*. The degree to which a job requires a variety of different activities in carrying out the work, which involve the use of a number of different skills and talent of the employee.
2. *Task identity*. The degree to which the job requires completions of a ”whole” and identifiable piece of work i.e. doing a job from beginning to end with visible outcome.
3. *Task significance*. The degree to which the job has a substantial impact on the lives or work of other people, whether in the immediate organization or in the external environment.
4. *Autonomy*. The degree to which the job provides substantial freedom, independence, and discretion of the employee in scheduling the work and in determining ”the procedures to be” used in carrying it out.
5. *Feedback from the job itself*. The degree to which carrying out the work activities required by the job results in the employee obtaining direct and clear information about the effectiveness of his or her performance.
6. *Feedback from agents*. The degree to which the employee receives clear information about his or her performance from supervisors or from co-workers.
7. *Dealing with others*. The degree to which the job requires the employee to work closely with other people in carrying out the work activities.

The key-factor of the work environment is influenced by the level of automation in various aspects. Regarding safety, there are two main points to consider. First, by implementing automation in a process, the operator transitions from an active role to a monitoring role, or even removes an operation from the process completely, which enhances safety [4]. While automation generally enhances safety, there are instances where it can have the opposite effect. For example, a worker who initially performed tasks manually and is now collaborating with a machine may face hazardous situations if they are given partial control over the machine. Second, in terms of physical ergonomics, automation can take on heavy tasks, leading to significant improvements in safety [50]. When it comes to job satisfaction, automation in manufacturing has reduced repetitive work, which is a major factor in worker dissatisfaction [51]. In addition to improving job satisfaction, the replacement of repetitive tasks with machines also positively impacts quality, as workers are prone to making mistakes during highly repetitive tasks [4].

As seen from the various terms and levels, the work environment is a complex system that cannot be assessed through a simple calculation and consists of multiple components. Safety and job satisfaction each have their own metrics and methods for assessment. To effectively conduct these assessments, the design should allow for easy evaluation. Assessments can be performed during the design stage, such as with 3D models, augmented reality [52] or other visual representations [53]. Once a concept for the design is established, test setups can be used to evaluate the work environment. Experts with knowledge of manufacturing work environments provide valuable insights into how different levels of automation impact workplace conditions.

2.1.3. Flexibility

The key-factor of flexibility, is highlighted by Neely et al. [34], as a crucial factor in literature on manufacturing which significantly influences the level of automation in production line design. When designing a production line, incorporating a certain level of flexibility is essential to adapt to changing environments. Upton [54] defines flexibility as ’the ability to change or react with low penalty in time, effort, cost or performance’. In essence, flexibility is the ability to adjust to changing circumstances, which aligns with the constant goal of improving a company’s objectives and overall output.

Flexibility can be classified by the object of variation for which flexibility is considered. Three dimensions are central in flexibility: the process, the product and the production volume [55]. The process flexibility is the ability to alter the production process by using different machines or paths through the factory. Product flexibility is the ability of a manufacturing system to efficiently adapt to changes in product types or designs, including the modification of existing products and the introduction of new variants. Production volume is the capacity to operate efficiently at different production volumes, scaling up or down as needed. By embracing flexibility, companies can better respond to market fluctuations and improve their competitive edge [56].

There are three basic levels of flexibility, as shown in Table 2.2. These levels correspond to the concepts of flexibility, reconfigurability, and changeability. All three levels address modifications in manufacturing systems, with differences in timing, cost, the number of modifications, and the steps required to implement these changes [57].

Table 2.2: Basic Flexibility levels from Terkaj et al. [58]

Basic flexibility level	Definition
Level 1 (Flexibility)	The system has the ability
Level 2 (Reconfigurability)	The system can acquire the ability already having the enablers
Level 3 (Changeability)	The system can acquire the enablers

The definitions of flexibility levels utilize the key concepts of ability and enablers. Enablers are tools, technologies, or features that facilitate adaptation in manufacturing systems. Examples include modular hardware, flexible software, and interfaces for upgrades. Ability refers to the system's capacity to respond to changes in production requirements, such as adjusting volumes, producing different products, or incorporating new technologies.

- At Level 1, the manufacturing system possesses the inherent ability to adapt to changes without needing additional modifications or resources. This system is designed with built-in capabilities that allow it to handle production variations seamlessly. This level represents the highest degree of flexibility, where no external enablers or interventions are needed.
- At Level 2, the system has integrated enablers in its design, allowing it to acquire the ability to adapt. These enablers, such as modular components or adaptable software, facilitate quick and efficient reconfiguration of the system to meet new production requirements. Reconfigurability provides a middle ground between flexibility and changeability, leveraging existing resources for adaptation.
- At Level 3, the system lacks the ability to adapt but can acquire it by introducing new enablers. This process requires external investments or modifications, such as adding new modules, upgrading equipment, or implementing new technologies. Changeability represents the most resource-intensive approach to achieving flexibility, as it involves obtaining and integrating new enablers into the system.

The trade-off between the level of automation and the flexibility of a production line is significant. Generally, human operators excel in flexibility compared to automated systems [4]. Humans can easily adapt to new circumstances, while machines often require adjustments that demand considerable effort and time. However, it's important to recognize that the flexibility of human operators should not be overestimated. Adapting to changing environments may also require skills training for workers who need to learn how to handle new tasks and adjust to evolving production conditions. Another trade-off to consider in this context is the investment in flexibility. Investing in modular automation systems can facilitate easier reconfiguration of production lines, but it often comes with higher upfront costs compared to fixed automation solutions. There are trade-offs in the dimensions of factor flexibility itself [59]. For example, a manufacturing system that is flexible in terms of volume may not be beneficial for the introduction of a new product.

Although the strategic importance of flexibility is generally well recognized, assessing its value when justifying investments in flexible manufacturing systems during the design phase can be challenging [58]. To address this, flexibility levels as outlined in Table 2.2can be utilized. As Terkaj et al. [58] state, when considering basic flexibility, these levels can be applied to different dimensions of flexibility, which Skinner categorizes as process, product, and production volume. When assigning different production line designs, the flexibility level for each dimension can be compared to evaluate the flexibility ratings across various designs. Since there is no standardized metric for each level, experts in the context of manufacturing can be consulted to estimate the flexibility levels for each dimension of the different designs. These scores on flexibility levels can be determined for specific parts of the production line, where design variations and differing levels of automation are present.

2.1.4. Cost

Another important key-factor to include in the evaluation of the trade-off between automation and human operators is cost [34] [35]. Decisions on automation and production systems are usually based on the relative costs of alternatives. Manufacturing costs can be divided into two main categories: fixed costs and variable costs. Groover [4] gives the following separation of fixed cost in manufacturing. Fixed costs remain constant regardless of the level of production and include expenses such as factory buildings, equipment, machines, insurance, and property taxes, which are usually calculated on an annual basis. The fixed costs in this equation are simplified as linear depreciation over a fixed period, without considering net present value (NPV). In contrast, the operational variable costs increase as production output rises. Examples of variable costs include direct labor, wear of machine parts and electricity needed to operate equipment. Ideally, variable costs are directly proportional to the level of output. It is important to note that the variable costs referred to in this context are operational variable costs, not the variable costs of materials.

The total annual cost of manufacturing can be calculated by adding the annual fixed cost and the annual variable cost. This gives the total cost equation as displayed in Equation 2.4.

$$TC(Q) = FC + VC \cdot Q \text{ [€/year]} \tag{2.4}$$

$$\begin{aligned} TC &= \text{total annual cost} && [\text{€/year}] \\ FC &= \text{fixed annual cost} && [\text{€/year}] \\ VC &= \text{variable cost} && [\text{€/piece}] \\ Q &= \text{annual quantity produced} && [\text{piece/year}] \end{aligned}$$

When comparing the costs of a manual process to those of an automated one, it becomes clear that the manual process has low fixed costs but high variable costs. In contrast, the automated process has high fixed costs and low variable costs. This difference arises because, in a manual process, labor costs, which are variable, are the highest. On the other hand, in an automated process, the cost of machines significantly increase the fixed costs. As illustrated in Figure 2.1, there is a break-even point at a certain production quantity where the automated process becomes more cost-effective than the manual one. While automation typically has higher fixed costs and lower variable costs compared to manual processes, there are exceptions. In some cases, automation can be cheaper from the start due to technological advancements or reduced labor reliance. In such scenarios, there is no break-even point, as automation remains consistently more cost-effective than manual approaches. In Figure 2.1, the x-axis can represent either quantity or time, depending on the analysis's purpose and intended message. When focusing on how production volume affects automation, using quantity as the independent variable highlights the direct relationship between automation efficiency and production scale. For example, automation may only be feasible or cost-effective at higher production volumes, showcasing its dependence on quantity. Conversely, if the aim is to evaluate investments, returns, or metrics like NPV, time is more relevant for the x-axis. This approach facilitates comparisons over a timeline, helping to determine when investments in automation pay off and how costs and benefits change over time, making it particularly valuable for financial planning and decision-making.

The difference in cost between manual and automated processes highlights a significant trade-off when deciding on the level of automation. A higher level of automation requires a larger initial investment, which can be a barrier for companies considering highly automated processes. Most of the times automated processes become more cost efficient over time, but production quantity is the component

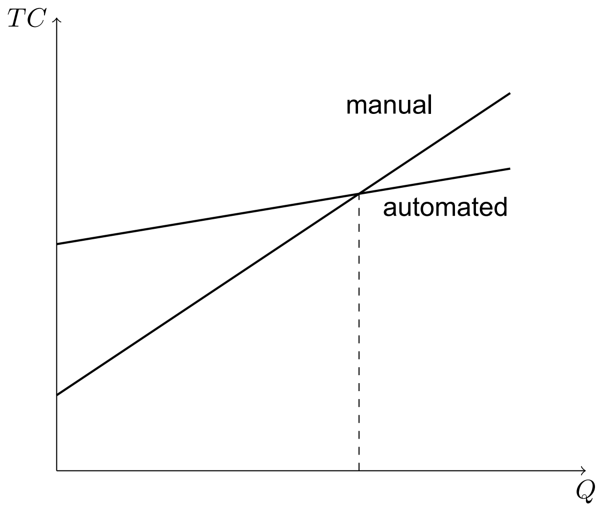


Figure 2.1: Total cost manual vs automated, based on Groover [4]

that determines this trade-off. If a production line is only expected to be in operation for a short period, a lower level of automation may be more appealing. However, if the production line is expected to run for many years, automation becomes more attractive due to its ability to lower variable costs, making the investment worthwhile over the longer lifespan. Ultimately, a higher level of automation is more cost-efficient than a lower level if the process will be used long enough to surpass the break-even point and yield greater overall savings.

Cost modeling is essential for evaluating the key-factors of cost in automation levels. These models predict costs based on factors such as production volume, resource allocation, and levels of automation. By utilizing cost estimation techniques, manufacturers can objectively compare the costs of manual and automated processes, identifying the most cost-effective option for their specific production needs. However, as highlighted in the literature search in the introduction, there is a significant drawback to relying solely on cost modeling to determine the optimal level of automation. This approach oversimplifies the operational aspects of a production line by focusing only on cost aspects of the automation trade-off. While cost modeling remains a crucial aspect of assessing automation levels, as it is a primary driver for companies making investment decisions, it is important to consider other key-factors. These include quality, work environment, flexibility, and production performance. Although some factors like quality and production performance can be translated into costs, cost alone should not be the sole metric for assessment. A comprehensive evaluation that incorporates these additional factors is necessary to make a well-rounded comparison between different levels of automation.

2.1.5. Production performance

The final important factor for assessing the level of automation is the production performance [35]. There are many metrics to assess production performance in manufacturing. To start with the most basic level of production performance, one can examine the separate performance metrics of production steps within the manufacturing process. Since a manufactured product is typically not completed in one step, it must pass through different production steps. The time it takes for a unit to be processed in a given process is called cycle time, which indicates the time required per production unit for that specific production process [4]. At this production step level in the manufacturing process, the production rate can be evaluated. This refers to the number of units a production step completes per hour [4]. When looking at a higher level of manufacturing, production capacity can be calculated. Production capacity is the maximum output that a production facility can achieve under a given set of assumed operating conditions, which include the operating hours of the manufacturing company [4].

$$OEE = Availabilty * Performace * Quality \tag{2.5}$$

$$Availabilyty = \frac{\text{scheduled time} - \text{downtime}}{\text{scheduled time}}$$

$$Performance = \frac{\text{actual production output}}{\text{theoretical production output}}$$

$$Quality = \frac{\text{good units}}{\text{good units + defective units}}$$

It is important to note that production capacity is a theoretical performance measure, as a manufacturing company never operates at 100% capacity. Overall equipment effectiveness (OEE) is a critical metric that indicates how well a company meets its production capacity [60]. Equation 2.5 gives an overview of the different components of the equation. OEE consists of three key elements: operational availability, performance, and quality rate. Operational availability measures the percentage of time that equipment is available for production, excluding both planned and unplanned downtime. Performance assesses how efficiently equipment operates compared to its maximum potential, taking into account speed losses and minor stops. Quality measures the rate of producing defect-free products and is closely related to the overall quality aspect, as lower quality levels result in fewer usable units being produced. An OEE of 85% is often considered the maximum achievable for a manufacturing company [60]. The actual production capacity is referred to as production volume, which is defined as the total units produced over a specific time period.

Table 2.3: Metrics overview production performance

Metric	**Definition**
Cycle time	The time it takes for a unit to be processed or assembled in a given process [minutes]
Production rate	The number of units a production step completes per hour [unit/hour]
Production capacity	The maximum output that a production facility can achieve under a given set of assumed operating conditions [unit/year]
Overall equipment effectiveness	The efficiency of a production process [%]
Production volume	The actual number of units produced by a production facility over a specific time period [unit/year]

The production performance metrics presented in Table 2.3 provide a comprehensive overview of the key indicators. The metrics have different scopes in the manufacturing process. Cycle time is measured at the lowest level per unit, production rate is assessed per production step, and production capacity is defined for the whole manufacturing process. To enhance these metrics, an important analysis is employed: bottleneck analysis. This analysis helps identify the limiting factors or constraints within a process or system that prevent it from reaching its full potential or optimal performance. The Theory of Constraints (TOC), developed by Eliyahu Goldratt [61], is an effective methodology frequently used alongside bottleneck analysis. TOC emphasizes the importance of identifying and optimizing bottlenecks within a process to enhance overall flow and performance. The core concept is that every system has a limited number of key constraints or bottlenecks that restrict its output. Addressing these constraints is essential for improving the system's throughput and efficiency. A constraint is anything that limits a system from achieving higher performance relative to its goals. When measuring production performance, it's important to consider the number of constraints present. To minimize the impact of these constraints and enhance production performance metrics, buffers are utilized around them. Buffers refer to the inventory or time allowances placed before a bottleneck to ensure that it consistently has work available. The size of the buffers can be used to assess the elevation of the constraints. By systematically addressing constraints using the TOC, organizations can improve their production performance.

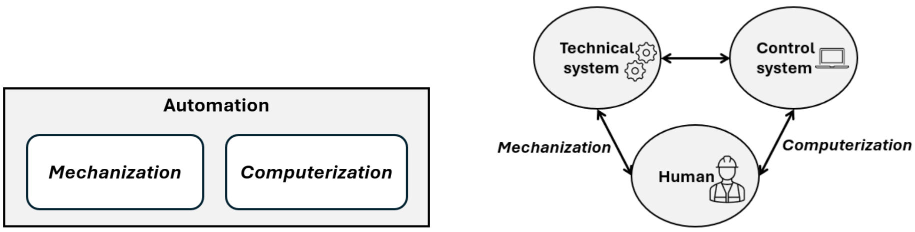
The level of automation significantly affects production performance metrics. As the automation of a process increases, the production rate tends to rise. This, in turn, enhances the production rate of a particular step. Additionally, because automated processes can operate continuously without breaks, the number of units produced increases, leading to improved overall production volume.

When assessing the trade-offs of different levels of automation in the production process, it is important to acknowledge the human factors involved in manufacturing that can influence performance metrics. Humans tend to be less consistent than machines. Additionally, one must consider that production volume is dependent on overall equipment effectiveness, which takes into account that up time, production output, and quality of units may not be at their maximum. This implies that production volume is stochastic rather than deterministic. To analyze production volume effectively, discrete event simulation is a useful tool for incorporating stochastic analysis. This simulation provides replication of the dynamic behavior of the proposed system, producing numerical performance indicators that enable informed judgments about the production performance of a manufacturing system [62].

2.2. Levels of automation

> *"There must be a simple way of showing where and how the human fits in the enterprise and how the distribution of functions between humans and machines is accomplished."*
>
> T.J. Williams, 1990 [63]

The trade-offs among key-factors in automation depend on the level of automation (LoA). The term "Level of Automation" refers to the division of tasks between humans and machines [64]. This division can take various forms and is reflected in different levels of automation within production [65]. At one extreme, there is complete machine operation, where the system operates autonomously; at the other extreme, there is a complete manual process. Automation can be categorized by tasks and behaviors. The tasks may be physical or cognitive, and the overall behavior of the system is a combination of these tasks. Automating physical tasks is referred to as mechanization, while automating cognitive tasks is called computerization. Mechanization involves transferring physical tasks from humans to technical systems [66], whereas computerization entails transferring cognitive tasks from humans to machines. The general concept of automation encompasses both mechanization and computerization [67], as illustrated in Figure 2.2a. In the end, automation relies on the connection between three elements: the technical system, the control system, and the human. These three components can work together to complete a task, as shown in Figure 2.2b.



(a) Connection between computerization and mechanization from Frohm et al.[67]

(b) Connection between automation, computerization and mechanization, adjusted from Frohm et al.[67]

Figure 2.2: Automation is a combination between mechanization and computerization

The levels of automation reflect the extent of mechanization and computerization in a given relationship. Frohm et al. [67] have defined seven levels of automation that are widely referenced in the literature. These levels are ranked from 1 to 7, where Level 1 represents total manual work and Level 7 corresponds to a fully automated system. The levels are associated with both physical and cognitive tasks, as illustrated in Table 2.4.

Table 2.4: Levels of automation from Frohm et al.[67]

LoA	Mechanical and equipment	Information and control
1	**Totally manual** - Totally manual work, no tools are used, only the users 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 earlier 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. Adjustable 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 machine that is designed for a specific task. E.g. Lathe	**Supervision** - The technology calls for the users' attention, and direct it to the present task. E.g. Alarms
6	**Flexible machine/workstation** - Automatic work by machine that can be reconfigured for different tasks. E.g. Computer numerical control 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 it self. E.g. Autonomous systems	**Totally automatic** - All information and control is handled by the technology. The user is never involved. E.g. Autonomous systems

The system designer should pay attention to the processes in case of which to be performed by the operator and which by a machine or both. Not all tasks can be performed at the extremes of being completely manual or completely automatic. Some operations may pose hazards or cause fatigue when performed by an operator, while others may lack a viable technical solution due to their complexity. The relationship between automation levels and the previously introduced concepts of mechanization and computerization is illustrated in 2.3. Finding the right balance between human interaction and automation involves considering the five key-factors: quality, work environment, flexibility, cost and production performance.

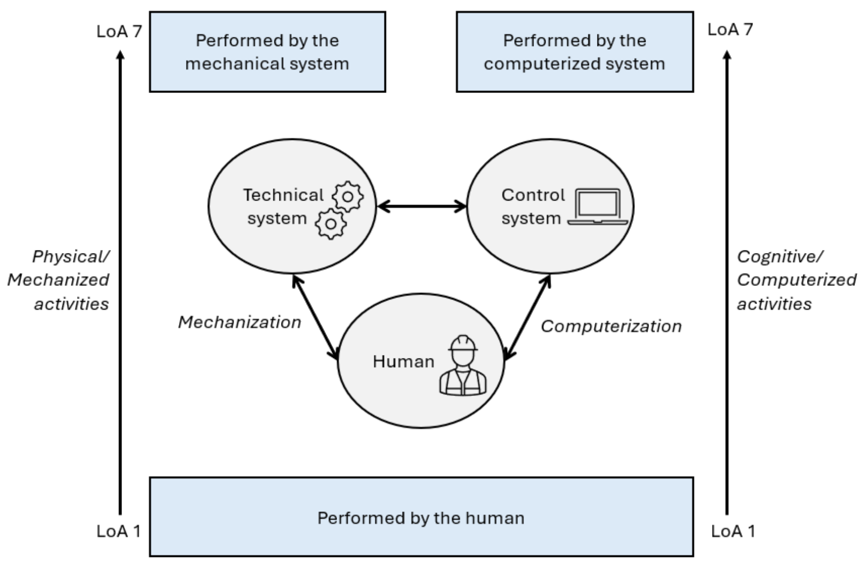


Figure 2.3: Connection between the LoA and the task allocation, adjusted from Frohm et al.[67]

3
Methodology for early stage automation evaluation

Building on the literature review in Chapter 2, which identified the key-factors and trade-offs influencing automation decisions, Chapter 3 introduces the methodology developed to systematically evaluate different levels of automation in production line design. Section 3.1 begins by outlining the overarching purpose of the methodology and explains how it has been refined through iterative feedback sessions. Following this, the preparatory steps required before applying the methodology, including contextual analysis and mapping of the production process, are detailed in Section 3.3. From Section 3.4 onward, the methodology is presented step-by-step.

3.1. About the automation evaluation methodology

Purpose of the methodology

The methodology presented in this chapter is designed for manufacturing companies that are in the early stages of designing a production line. Many factors influence the final design, and this methodology specifically focuses on the level of automation within the production line.

Since it is centered on the early stages of design, the methodology aims to provide insights into how different automation levels affect the production line. The goal is to highlight the trade-offs between various automation scenarios. This framework serves as a conceptual model to support early stage thinking, helping to structure ideas through data and dialogue.

The automation evaluation methodology is designed to identify the trade-offs that arise at different levels of automation. To illustrate these trade-offs, five key-factors identified in the previous chapter are: quality, work environment, flexibility, cost, and production performance.

Methodology refinement trough feedback sessions

In this chapter, the complete steps of the automation methodology are presented. The version outlined here represents the final iteration, refined through a rigorous design science approach. This final version of the methodology is the result of three feedback sessions. Information about how the feedback sessions were held and how these sessions contributed to this final version is extensively discussed in Chapter 5.

3.2. Overview of the automation evaluation methodology

To create the automation evaluation methodology, a design science approach is utilized. The first step of this approach involves problem identification and motivation, which is detailed in Chapter 1. This process led to recognizing the need for a methodology that systematically addresses the trade-offs encountered when determining the appropriate level of automation in early-stage production line design.

Following this identification, the second step of the design science approach, outlined in Chapter 2, involves establishing the objectives for the solution. Here, key-factors representing the trade-offs between different levels of automation are identified. The third step of the design science approach is the design and development of an artifact, which in this case is the automation evaluation methodology. This step is based on two main outcomes derived from the objectives: a combination of quantitative and qualitative metrics for assessing the trade-offs associated with varying levels of automation within production line design.

An overview of the steps involved in the automation evaluation methodology, along with the reasoning behind each step and the criteria for their inclusion, can be found in Table 3.1. This section will further discuss the rationale for each step. Additionally, since evaluating the artifact is a crucial element of the design science approach, some steps were modified based on feedback received during the evaluation process. The changes made to the automation evaluation methodology as a result of these feedback sessions will be discussed in Chapter 5.

Table 3.1: Overview steps automation evaluation methodology

Step	Step content	Motivation	Grounds
0	Documenting of context, requirements, and production steps.	Ensures context is considered and preparations are complete.	- Design Science; objectives and context must be identified [30]; - Feedback sessions highlighted the need for company-specific elements.
1	Creation of low, medium, and high automation scenarios.	Systematically explore and compare feasible automation options, ensuring balanced decisions that align with key-factors.	-Key-factors [34][35] and levels of automation [67] form the basis for the automation evaluation methodology.
2	Development of conceptual models and layout maps.	Makes automation scenarios concrete and understandable for effective comparison and evaluation.	-Conceptualization is essential for comparing production line designs [23].
3	Creation of dynamic models and experiments.	Quantitative key-factors require modeling; Dynamic, because hybrid systems combine machine and human elements.	-Quantitative metrics of the key-factors; - Modeling is commonly used in manufacturing to review production lines [68].
4	Comparison of automation scenarios by key-factor based on model outcomes, cost modeling, and expert input.	Clarifies trade-offs between key-factors and shows how automation levels affect each factor.	- Cost modeling is one of the most used approaches to assess production line design [10]; - Qualitative factors require a qualitative expert approach.
5	Synthesizing of insights from all automation scenarios to clarify trade-offs and guide the selection or refinement of the best solution.	Combining insights for each key-factor across scenarios makes trade-offs clear and supports decision-making.	- Feedback sessions indicated need for a structured trade-off conclusion.

The methodology begins with Step 0, which involves documenting the context, requirements, and production steps. The reasoning behind this step is to ensure that the specific context is fully considered and all necessary preparations are complete before moving forward. This foundation is crucial, as it guarantees that subsequent decisions are grounded in the actual needs and constraints of the manufacturing system. In Step 1, low, medium, and high automation scenarios are created. This step is designed to systematically explore and compare feasible automation options, making it possible to consider a broad range of solutions. By categorizing scenarios according to key-factors and levels of automation, the methodology supports identification of balanced automation options. Step 2 focuses on the development of conceptual models and layout maps. The reasoning here is that making automation scenarios concrete and understandable is essential for effective comparison and evaluation. Visualizing the structure and flow of each scenario clarifies their differences and potential integration challenges, providing a clear basis for further analysis.

The next phase, Step 3, involves the creation of dynamic models for the automation scenarios and doing experiments with these models. This step is grounded in the need for quantitative analysis of key-factors such as throughput, resource utilization, and bottlenecks. While static models and spreadsheets can offer calculations for average throughput, resource utilization, and costs, they are fundamentally limited to steady state or aggregated views and cannot illustrate how the system behaves as events unfold over time. By modeling the dynamic behavior of each scenario, the methodology provides a data-driven foundation for comparing their performance under realistic operating conditions. Simulation, particularly discrete event simulation (DES), plays a vital role in the analysis of manufacturing systems [69]. It captures the dynamic and time-dependent interactions, along with the operational complexities, that static tools such as spreadsheets cannot effectively represent. DES models break down production workflows into distinct sequences of events, allowing for explicit modeling of variability and dependencies, as well as factors influenced by operators, such as skill differences, communication, and break schedules. This methodology enables the examination of how disruptions or changes in one part of the system create ripple effects, like bottlenecks, idle times, or resource conflicts, throughout the process capabilities that static models lack. Moreover, DES can include complex logic, such as prioritizing tasks, simulating operator fatigue, and modeling the effects of shift changes or machine failures. These features are essential for understanding real-world manufacturing environments where variability and inter dependencies are common. Simulation environments enhanced by 3D animation provide additional clarity by visualizing operator movements, material flows, and layout effectiveness insights that cannot be derived from spreadsheet calculations alone. Ultimately, DES offers a virtual testing ground for experimenting with various automation scenarios, predicting the impacts of changes, and optimizing system performance without disrupting actual operations or incurring unnecessary costs. This makes simulation crucial for informed decision-making in complex manufacturing systems.

Step 4 is dedicated to the comparison of automation scenarios by key-factors, based on model outcomes, cost models, and expert input. The purpose here is to clarify the trade-offs between the automation scenarios, considering both quantitative results and qualitative expert assessments. This comprehensive evaluation ensures that all relevant aspects are systematically compared. Finally, Step 5 synthesizes insights from all automation scenarios to clarify trade-offs and guide the selection or refinement of the best solution. By combining findings for each key-factor, this step supports informed decision-making and provides a structured basis for iteratively refining the automation strategy to best suit the organization's needs

3.3. Step 0. Preparations before starting the methodology

The design of a manufacturing system is heavily influenced by its specific context. Each case is unique, shaped by factors such as the type of product being produced and the characteristics of the company. This context presents both opportunities and constraints that affect the design of the system and the level of automation that can be implemented. For instance, some companies may prioritize sustainability, while others might focus on product quality, or operate under strict budgetary constraints. Before applying the methodology, it is essential to identify the context-specific constraints, which often determine the development of the manufacturing system and create the solution space of the application of the methodology. The solution space can be divided into constraints, requirements, and wishes for each key-factor, as well as considerations that fall outside of these key-factors. For each category, the examples of aspects, are listed in Table 3.2 to be considered, but more can be taken into account as this is very context depended.

Table 3.2: Overview of Categories and Requirements

Category	**Requirement**
Production performance	Annual production volume Overall Equipment Effectiveness target
Cost	Maximum investment costs Maximum payback period
Quality	Quality requirements Quality control requirements
Work environment	Minimal safety requirements Labor policies Mission/vision alignment
Flexibility	Needed flexibility in production process Flexibility in production volume Flexibility in future product changes Different type of products to be produced
Other considerations	Start time of going live Expected time span of production line Regulatory compliance

Another vital preparation step involves having a clear and comprehensive understanding of the manufacturing system being analyzed. The goal is to have a clear overview of the execution order of production steps and the techniques used at each step. The level of automation and a clear mapping of the process can be established later if this is not already available, as this is an integral part of the methodology. These two steps: the requirements, constraints, and wishes, as well as the production steps; need to be documented so they can be used as a backbone when applying the methodology, serving as a reference for the solution space of the production line.

3.4. Step 1. Creating different automation level scenarios of the production line

3.4.1. 1a. Identifying automation level alternatives per production step

In order to open up the discussion about the automation options considered for each production task, a first crucial step is to establish the acceptable minimum and maximum parameters for automation. This evaluation should align with the levels of automation discussed in Section 2.2. In this methodology, it is important to distinguish between physical and cognitive automation levels for each production step. Cognitive automation focuses on information processing and decision making, effectively taking over the brains of the human by transferring cognitive tasks such as analyzing data, making judgments, and controlling processes from humans to machines. In contrast, physical automation is concerned with the body of the human, as it involves the mechanization of physical tasks such as moving, assembling, or manipulating materials, thereby transferring these manual activities from humans to technical systems. By separately assessing both cognitive and physical automation levels, the methodology ensures a comprehensive evaluation of how automation can impact each production step, addressing both the mental and physical contributions of human workers.

For every production step, it is essential to assess both the range of physical automation level and the cognitive automation level the automation option should be in. This approach encourages the design team of the production line to focus on the overarching levels of automation from the outset, rather than jumping directly to specific solutions for each step. Not all production steps will have a range of automation levels. This may occur because there is only one option considered for a step, which could be the result of current practices or such as safety considerations. These steps do not have a range for the level of automation; instead, they are regarded as fixed steps that are not subject to different levels of automation. Therefore, these steps of the production line will not be considered in terms of automation level and are fixed to a set automation level throughout the entire methodology.

It is important to note that the ranges for automation should always reflect only the feasible options that are considered realistic and applicable within the company. While this methodology aims to broaden the perspectives on automation and encourage creative thinking, it is crucial not to lose sight of practical constraints. Maintaining a balance between exploring new possibilities and keeping the options realistic ensures that the outcomes of the methodology remain actionable and relevant. If the options become too theoretical or unrealistic, it is not likely they will be seriously considered or implemented by the organization. Once the automation ranges for each task have been identified, the next step is to define specific, feasible alternatives for automation levels within those established minimum and maximum boundaries.

A production process consists of several production steps, within each step, multiple tasks can be executed. These tasks may involve cognitive or physical activities. For each task a range of level of automation can be specified. This approach generates concrete options for each production step, illustrating the spectrum of possible automation solutions. An example illustrating this concept is provided in the section below.

Example identifying automation level ranges
For this example a production step of palletizing boxes is used. In the palletizing step of a production process, multiple tasks are executed that can be cognitive or physical. For this example, let's assume that the palletizing production step consists of three distinct tasks. There is one cognitive tasks: deciding which pallet each box should be placed on. In addition, there are two physical tasks: lifting the box onto the pallet and wrapping foil around the pallet once it is filled. This illustrates how a single production step can encompass multiple tasks, each requiring different types of cognitive and physical effort.

- *Cognitive task*: deciding which pallet the box should be placed on
  - LoA 2 - LoA 7
  - Operators need basic information to determine the appropriate pallet for each box.
- *Physical task*: lifting the box onto the pallet
  - LoA 4 - LoA 6
  - Minimal automated hand tool for ergonomic reasons.
- *Physical tas*k: wrapping foil around the pallet
  - LoA 6 - LoA 7
  - Both semi-automatic and fully automatic solutions are commercially widely available and are used within the company.

Once the automation ranges for each step have been identified, the specific feasible alternatives for automation levels within the established minimum and maximum ranges are defined. This process will provide concrete options for each step, showcasing different levels of automation.

In this example, two options are identified for the production step. The first option involves a lower level of automation, where an operator uses a vacuum tool to lift the boxes and follows a paper checklist to determine which pallet the box should be placed on, as illustrated in Figure 3.1a. And this options included a wrapping machine for the pallet once it is filled in as shown in Figure 3.1b. The second option features an automated palletizing machine that makes autonomous decisions and includes a built-in wrapping station, as shown in Figure 3.1c.

This example illustrates the various levels of automation available for a specific step in a production line. While some options may be dramatically different, others may be quite similar. When the range of automation levels for all steps in the production line has been determined and translated into specific automation options, the next sub-step can be initiated.

(a) Vacuum assisted lifting with paper checklist [70]

(b) Pallet wrapping machine [71]

(c) Automated palletizing machine with autonomous decision making [72]

Figure 3.1: Various automation options for a single production step

3.4.2. 1b. Developing automation level scenarios for the production line

Once the specific automation options for each production step have been identified, these options are organized into different automation scenarios. Creating different automation scenarios clarifies options and makes them relatable. It stimulates imagination, clarifies the overall situation compared to individual steps, and demonstrates how the various steps are interconnected. To define the range of automation levels, predefined absolute values of the levels of automation identified by Frohm et al. [67] are applied to ensure consistency across the assessment. However, the scenarios created at this stage categorize the various automation options into context-specific levels: low, medium, and high automation. The use of level of automation scenarios allows for a systematic exploration and comparison of feasible automation options. This categorization is highly context-dependent; in some situations, what is considered a ”high” level of automation might be relatively low, while in others, it may represent a very advanced automation state. Therefore, the interpretation of low, medium, and high automation levels is tailored to the unique circumstances of each case.

To categorize specific automation options for each production step, each option is evaluated systematically against five key-factors that are introduced in Section 2.1: flexibility, work environment, quality, production performance, and cost. For every step, the lowest logical level of automation, meaning it meets the minimum requirements of all five factors, is assigned to the low automation scenario. Conversely, the highest logical automation option is selected for the high automation scenario. The medium scenario is determined by choosing a balanced option based on these key-factors or, if no clear choice is evident, by applying a defined cost threshold.

The assignment of scenarios is conducted during an expert session, where trade-offs between key-factors are identified and documented. For example, the lowest automation option might offer high flexibility but has excessive labor costs, making it financially unsustainable. In such cases, the minimally viable option could shift to the second-lowest automation level to keep all the options in acceptable ranges. The trade-offs that are encountered when assigning the automation options to the level of automation scenarios, should be documented in a structured manner. This practice ensures that the organization maintains a clear record of decisions that outlines the reasons for selecting or rejecting specific levels of automation. Preserving this knowledge is essential, as it allows future teams designing production lines to build on previous insights rather than repeating analyses. For instance, if a past team decided against low automation due to fluctuations in labor costs, new teams can focus on improving higher automation options without having to review things that are already discussed.

By systematically evaluating each automation option against five key-factors, the scenario approach ensures that decisions are balanced across all key-factors rather than being dominated by a single aspect. This method also encourages teams to broaden their perspectives by exploring automation options they might not have initially considered, prompting them to think beyond traditional solutions and assumptions. For example, a team might discover that a slightly higher level of automation improves both quality and the work environment without significantly increasing costs. This is a trade-off, they may not have recognized without this structured evaluation. This comprehensive assessment supports well thought options and grounds each scenario in practical reality, as only those options that are logical and acceptable on all fronts are considered for implementation.

A significant limitation of scenario development is that the decisions made during the creation process strongly influence subsequent evaluations. Illogical or inconsistent choices made at this stage can propagate through the entire assessment process, potentially skewing the results. The methodology also relies on the availability of accurate data and expert judgment to evaluate each option, which introduces subjectivity and potential bias. Additionally, the approach assumes that all relevant automation options have been identified and that their impacts can be reliably assessed using key-factors. In reality, there may be unknown variables or unforeseen interactions between steps that are not captured in the scenario framework. It is advisable to allow for iterative revisions and updates as insights reveal that certain options may become unfeasible or as inconsistencies are detected during later stages of the assessment.

After selecting options for each step, they are combined with the predefined steps where automation options are already established to create three coherent automation scenarios for the entire production line. A final review ensures that the combination of steps in each scenario forms a logical and feasible whole, with any necessary adjustments made to incompatible or illogical combinations. This approach results in three complete and internally consistent automation scenarios: low, medium, and high, each representing a distinct level of automation for the production line.

3.5. Step 2. Conceptualizing the different automation level designs

After defining the automation scenarios, the next step involves conceptualizing these scenarios through developing detailed conceptual models and layout maps. This conceptualization step is performed to transform abstract automation scenarios into concrete, structured and visual representations that stakeholders can more easily understand and evaluate. This conceptualization of the different scenarios serves a twofold purpose. First, by working through the scenarios using the conceptualization methods, designers are encouraged to actively consider the various levels of automation, how they interact, and the relationships between different production steps. Second, the conceptual diagrams and layout maps created during this stage provide a foundational basis for comparing the scenarios in the later phases of the methodology.

The purpose of conceptual modeling is to define the boundaries of a system by describing the components, relationships, properties, and behaviors included, as well as identifying the necessary concepts to describe them. One effective conceptual modeling technique is IDEF0. IDEF0 is a structured graphical method used to represent the functions, processes, and interrelationships within a system. It utilizes diagrams to illustrate how inputs, controls, outputs, and mechanisms interact to perform activities. An IDEF0 model consists of interconnected diagrams, making it particularly useful for illustrating activities within a manufacturing system and how these activities interact over time [73]. One potential risk of conceptual modeling is that the model can become overly complex, making it difficult to understand and analyze. A model that is too simplistic might overlook essential information needed to address the problem effectively [74]. IDEF0 helps reduce the risks associated with improperly setting of boundaries by allowing for the creation of a small model that can be incrementally expanded. The hierarchical nature of IDEF0 enables step-by-step refinement, facilitating a systematic mapping of the process. In Figure 3.2, a visualization of the different elements of IDEF0 is presented for each activity, along with the decompositions of the various scheme levels.

While IDEF0 is highly effective for conceptual modeling, other techniques, such as Material and Information Flow Analysis (MIFA), are also employed in real-world manufacturing settings. MIFA is useful for optimizing material and information flows in accordance with lean principles [75]. In this methodology, IDEF0 is chosen for its hierarchical structure and its ability to provide a clear, graphical representation of the functions, processes, and interrelationships within a manufacturing system. Ultimately, the choice of modeling technique should align with what is most familiar and effective for the organization, allowing companies to utilize IDEF0, MIFA, or another appropriate method that best fits their needs and internal practices. However, this methodology continues with IDEF0, because of its hierarchical structure and clear graphical representation. For each automation scenario, an IDEF0 model should be developed to capture the functional structure and interactions.

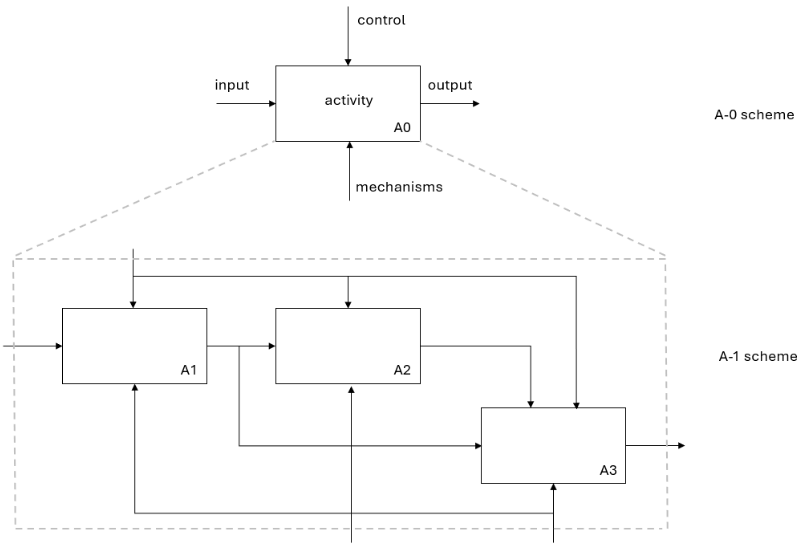


Figure 3.2: Decompositions of activities in IDEF0

Next, layout maps are developed to provide clear spatial representations of production lines. When designing these layouts, it is crucial to consider things as space constraints, the arrangement of transport systems, the width and accessibility of walking paths, and the physical size and placement of machines. Unlike highly detailed and optimized CAD models used for finalized production lines, these conceptual layouts serve as a tool for thinking through the impact of automation on the overall arrangement, helping to identify what is feasible and what may present challenges. Since there are many possible ways to translate IDEF0 process models into spatial layouts, the process requires careful judgment and iteration. To evaluate whether a proposed layout is workable, an advised approach is to print the layout at a large scale and have the production line design team simulate workflows using tokens to represent operators and products, moving them through the space according to a realistic time frame. This hands-on simulation helps to verify whether the initial layout supports an efficient production flow and highlights areas that may require further refinement. By combining IDEF0 models with these layout maps and practical simulations, the methodology enables a focused analysis of both the functional processes and the spatial organization within each scenario, ensuring that design decisions account for operational flow as well as physical feasibility.

The conceptualization of automation scenarios using IDEF0 models and layout maps provides a valuable structural foundation but has inherent limitations in capturing the full complexity of automation systems. While these conceptual models effectively represent the static elements and spatial arrangements of the production line, they focus primarily on specific elements like functional relationships and physical layouts without fully addressing the dynamic behavioral aspects of the automation scenarios. Therefore, the next step in the methodology involves creating a dynamic model.

3.6. Step 3. Developing dynamic models and addressing bottlenecks

3.6.1. 3a. Development of dynamic models

The next step in developing models for various automation scenarios is to move beyond static representations of the automation scenarios and create a dynamic model, specifically a discrete event simulation (DES) model. While conceptual models such as IDEF0 diagrams and layout maps are useful for outlining functional flows, data, and system boundaries, they are static and cannot capture the time-dependent interactions, variability, and operational dynamics that are inherent in real manufacturing environments. The static conceptual model technique IDEF0 and the dynamic DES model complement each other well: static models help to understand the structure and function of a system, while simulation enables dynamic analysis of its behavior over time [76].

A DES model addresses these limitations of the static models by breaking down the workflow into a sequence of distinct events, each occurring at a specific point in time. This approach forces designers to consider aspects often overlooked in static models or spreadsheets, such as operator flexibility, skill differences, communication between operators, break schedules, and dependencies between process steps. For example, DES can explicitly model how operators interact with machines, how their skills and fatigue levels influence task durations, and how breaks or shift changes introduce variability into the system. The task sequences of operators can be effectively implemented in a dynamic model by assigning different tasks with varying priorities to the operators. However, capturing the added value of the modeling of interactions among operators on the production line is challenging, as it can be time consuming to determine how to model these interactions. For example, one of these challenges is that it is essential to ensure that tasks are executed in the correct order by the operators within the dynamic model.

DES models can capture these hybrid automation realities, making it possible to analyze how fluctuations in one part of the system create bottlenecks or idle times elsewhere. This level of detail is crucial for identifying where buffers are needed, what happens when a buffer runs empty, and how these dynamics impact the overall flow and reliability of the production process [77]. While the initial DES model may remain relatively simple, using a simulation environment with 3D animation, such as Simio, helps stakeholders better understand and compare different automation scenarios [78]. The animation also shows that the various scenarios truly come to life, which is beneficial for creating insights about different automation scenarios. Additionally, the animation of the workers throughout the production line can also be used to assess the working conditions of the operators. Another advantage of the animation is that the layout maps created in the previous steps, which serve as the basis for the scenarios in the dynamic model, can be tested for accuracy. The animation can demonstrate whether the operators follow logical routes and how the transportation of semi-finished products occurs between the different production steps.

DES is chosen for its flexibility and ability to model complex, real-world scenarios, allowing for experimentation and optimization of different automation scenarios in a risk-free virtual environment. DES enables manufacturers to predict the impact of changes, identify bottlenecks, and evaluate alternative configurations without disrupting actual operations or incurring unnecessary costs [79]. The process of building a DES model begins with translating the steps identified in the IDEF0 diagrams and layout maps into simulation entities, machines, operators, and transport form the backbone of the model. Input data such as the number of stations, cycle times, resource availability, and failure rates are required to accurately reflect the system.

Verification and validation

Applying DES in early design stages comes with challenges: the quality of the simulation depends on the accuracy of input data and the validity of assumptions, which can be difficult to estimate at this point in the design process [80]. Managing these uncertainties and ensuring the model remains both representative and manageable are critical for deriving actionable insights. Therefore model validation and verification are important elements of these steps.

A comparison for verification of the simulation model can be executed by evaluating the number of entities created by the assembling stations against the theoretical maximum output, which is determined by operator working hours and process times. This comparison helps to assess whether the model's production rates are realistic. Additionally, the number of entities leaving the system can be compared to the number created, including both completed products and those rejected at quality checks, to ensure that the model accurately tracks all entities through the system. Any observed discrepancies, such as differences between entities created and destroyed, may indicate issues with buffer modeling or the length of the warm-up period and should be carefully analyzed.

To further confirm the logical flow within the model, the time entities spend in the system can be compared by tracing individual entities and matching their journey to the average, minimum, and maximum times recorded. This ensures that entities follow expected paths without unusual delays. Finally, applying Little's Law allows for a comparison between the average number of entities in the system, the arrival rate, and the average time in the system [81]. Little's Law states that the average number of items in the system (L) should be equal to the arrival rate (λ) multiplied by the average time an item spends in the system (w) as shown in Equation 3.1

$$L = \lambda \times w \tag{3.1}$$

These comparisons collectively provide a robust verification that the model's implementation aligns with theoretical expectations and logical system behavior. Model validity refers to how accurately a model represents the process it is designed to simulate. In this scenario, face validity is particularly relevant because the new production line lacks operational data, making traditional validation methods such as comparing outputs to real world data impossible. Face validity ensures that the model appears realistic to domain experts through a superficial examination of its structure, parameters, and logic. Experts can evaluate key aspects like machine cycle times and buffer sizes to verify their alignment with practical constraints. This approach enhances credibility by identifying unrealistic assumptions or overlooked factors that purely statistical methods might miss. Although face validity does not guarantee accuracy, it provides essential initial confidence in the model's quality of representation when empirical validation is not feasible [82].

3.6.2. 3b. Identifying and addressing bottlenecks

The next sub-step of the methodology focuses on identifying and addressing bottlenecks, which is is a crucial element of production line design because bottlenecks directly limit the overall throughput and efficiency of the system. When a bottleneck occurs, whether due to a machine with minimal capacity, high failure rates, or production segments where human involvement introduces variability, it causes work to accumulate, leading to delays, increased costs, and underutilization of resources across the production line. By pinpointing these critical constraints, manufacturers can strategically allocate buffers and adjust workflows to smooth production flow and prevent disruptions.

Bottleneck analysis is essential for optimizing production systems. The Theory of Constraints (TOC) provides a structured five-step approach to systematically improve throughput [61]:

1. *Identify the constraint*: Pinpoint the process step that limits overall output, such as a slow machine or a restrictive policy.
2. *Exploit the constraint*: Maximize the bottleneck's output by minimizing downtime and ensuring it operates at full capacity.
3. *Subordinate other processes*: Align all non-bottleneck activities to support the constraint, which may include adjusting workflows or automating tasks like transport to free up workers.
4. *Elevate the constraint*: Invest in upgrades, such as adding machines or improving maintenance, to eliminate the bottleneck.
5. *Repeat*: Continuously identify and address new constraints as the system evolves. There will always be a bottleneck; when one is resolved, another will present itself.

The process of continuously adjusting and aligning workflows is already common practice in manufacturing and plays a crucial role in adapting to real-world conditions. However, to analyze and optimize it effectively, a dynamic model is essential. DES models are crucial in this process, as they allow for inclusion of variable elements and sensitivity testing and experimentation with different scenarios. For example, analyzing how changes in bottleneck performance (such as machine speed or reliability) affect overall production helps uncover hidden inefficiencies or unexpected dependencies. For complex machine, sensitivity analysis should use broader parameter ranges to account for unpredictability.

3.6.3. 3c. Performing experiments

With the dynamic model, many experiments can be conducted. In this methodology, four types of experiments are advised: a sensitivity experiment, a disturbance analysis, a volume flexibility experiment, and an OEE calculation. The experiment on the OEE calculation is discussed in step four Section 3.7.1: production performance comparison.

Before conducting the experiments it is important to design an experimental framework. This includes multiple replications and a warm-up period. The replications are needed for the increase off the reliability of the outcomes of the experiment as they allow for estimation of variability and enhance the reliability of the results by reducing the impact of random errors. A minimal of 10 repetitions is advised to use to create reliable results. The warm-up period is needed to simulate a filled production line as most of the times a production line does not start up completely empty at the start of the day.

The sensitivity experiment in manufacturing simulation is used to assess how changes in key input parameters, such as the cycle time at bottleneck steps, impact total production output. This can be incorporated into the model by adjusting the process times and examining the impact on the average daily production volume.

The disturbance experiment provides insight into the impact of downtime at a station on the overall production line. This can be conducted for specific stations of interest by allowing them to fail for a predefined duration, such as 15 minutes, and observing the effect on total production volume. It is advisable to focus this analysis on the bottlenecks identified in the previous step, as these are critical points in the production line that can significantly affect overall performance.

The flexibility experiment can be conducted by adding capacity at the beginning of the production line to enhance supply for the entire line. This is done to determine the maximum output the line can handle. This involves gradually increasing the capacity until no further improvements can be observed. For example, a higher level of automation can process more additional products than a lower level. This increase can be measured by the total daily production volume.

3.7. Step 4.Comparing the different automation level scenarios per key-factor

The goal of this methodology is to clarify the trade-offs between different levels of automation in the design of a production line. In the fourth step, the impact of different automation levels on key-factors is examined, allowing for direct comparisons across various automation scenarios. This step explains how comparisons can be made for each key-factor. For the key-factors of operational performance and cost, which have a more quantitative nature, a quantitative approach is taken.

In contrast, for the more qualitative factors such as quality, work environment, and flexibility, a relative comparison is utilized during a review session. Here discussion points are provided to help experts discuss various automation scenarios, enabling them to generate insights on automation levels and identify potential improvement areas for different designs.

Improving production line design based on ALARP principle

A well-known technique for finding improvements in designs is the ALARP principle. ALARP, an acronym for ”As Low As Reasonably Practicable,” is a key principle in risk management that emphasizes the need for organizations to minimize risks to a level where any further reduction would require an unreasonable amount of effort, time, or cost [83]. The ALARP region is situated between unacceptable and broadly acceptable risk levels. Within this framework, organizations should strive to lower risks as much as reasonably achievable while balancing these efforts against available resources, such as cost and effort as illustrated in Figure 3.3.

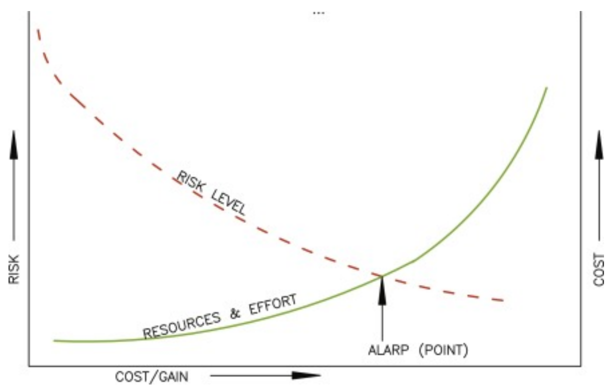


Figure 3.3: ALARP figure from [84]

Although traditionally linked to safety, the ALARP principle can be applied in a wider context [85]. In the context of this automation methodology, risk encompasses not just the likelihood of safety incidents but also factors such as quality, work environment, and operational flexibility. The aim is to implement design improvements that deliver meaningful benefits with reasonable effort, while recognizing the point at which further enhancements would require disproportionately greater investment of resources.

For instance, when examining the risk of product quality falling short of specified requirements, organizations can leverage the ALARP principle to find solutions that mitigate this risk while using the least amount of resources possible. In this manner, ALARP serves as an effective tool for guiding improvements across various domains, ensuring that advancements are sought only up to the point where further progress requires substantially greater investments relative to the benefits anticipated.

3.7.1. Production performance comparison

The operational performance key-factor can be effectively analyzed using the dynamic models, for the different automation scenarios, created in the previous step. The primary focus of operational performance is the production volume, which can be expressed per day, week, or year. This data can be directly generated by the DES model. The production volume should be compared against the initially defined daily production target for the production line. If this target is not met, the underlying causes must be identified to provide the necessary insights. This could include issues such as bottlenecks or inefficient resource usage. The bottleneck analysis from Step 3b may already have highlighted the reasons why the expected production volume is not achieved.

Another commonly used indicator of operational performance is the Overall Equipment Effectiveness (OEE). OEE is calculated by multiplying three components: availability, performance, and quality. The calculation of OEE is explained in Section 2.1.5. OEE can be calculated at different levels, such as the station, production step, or production line. However, this methodology specifically focuses on the entire production line; therefore, OEE is determined at the production line level.

The first thing OEE is based on is the availability of the production line, which requires data on scheduled time and downtime. To obtain this data from the DES model, failure rates per production step must be incorporated during model development. In practice, this can be challenging in early stages, as estimating failure rates without test runs is often difficult. Therefore, estimations are typically required. For estimations, FMEA (Failure Mode and Effects Analysis) and MTBF (Mean Time Between Failures) can be used. FMEA is a systematic approach that identifies potential failure modes in a machine or process, identify their causes and effects, and prioritizes them based on risk, helping to estimate and reduce machine downtime by addressing the most critical issues. MTBF is a quantitative reliability metric that calculates the average time between equipment failures, allowing organizations to predict how often downtime might occur and to plan maintenance schedules accordingly.

The second component of OEE, quality, calculated using the number of good units versus defective units, is also difficult to determine without real-world data. Here too, estimations are necessary. The final factor of OEE is performance, which measures actual production output relative to maximum possible output. This is influenced by both the availability and quality of the production line. The actual output, derived from the production volume in the simulation, can be used to calculate performance. When availability, quality, and performance are combined, the OEE is calculated as their product.

The higher the OEE, the better the production performance. An OEE of 85% is typically regarded as the maximum achievable level for a manufacturing company [60]. In reality, most production lines fall short of this benchmark, especially during the ramp-up phase, where OEE can be significantly lower. In practice, an OEE score of around 60% is quite common among manufacturers, indicating that there is considerable potential for improvement. For companies that are just beginning to monitor and optimize their manufacturing performance, an OEE score of 40% is not unusual [86]. If certain automation scenarios yield lower OEE values, further investigation is needed to determine whether downtime, failures, or other factors are responsible. These insights should be mapped to the corresponding automation scenarios and production steps. Once this mapping is complete, the analysis can proceed to comparisons with the next set of key-factors.

In reality, because the production line is still in its early design stage and the machines are not fully identified, the estimates for OEE may not be very reliable. Since there are many assumptions involved, OEE might not be the best way to compare production performance. In the end, the average production volume gives a clearer picture of what different automation options can achieve.

When an OEE value is still desired but the necessary data is unavailable, working with assumption ranges can provide a solution. By defining upper and lower bounds for unknown parameters (such as failure probabilities, changeover times, or quality percentages), a bandwidth for the OEE outcome emerges. This approach shifts from a definitive OEE per scenario to a risk-driven OEE calculation, highlighting which assumptions or parameter values cause performance to fall below minimum requirements. This is a type of deep uncertainty analysis where parameters with unknown distributions are assumed to have equally probable values across a defined range. By systematically varying these ranges and analyzing outcomes, organizations gain visibility into all potential future situations. This enables identification of high-risk areas and reveals whether certain scenarios will consistently fail to meet requirements.

3.7.2. Cost comparison

The cost comparison is based on the fixed and variable costs per step, as defined in Section 2.1.4. Using the input values for the expected annual production rate, the expected lifespan of the production line, and the estimated fixed and variable costs, a cost comparison can be performed for different automation levels across steps and scenarios. Fixed costs typically include expenses such as machine costs, engineering fees, and installation expenses. In contrast, variable costs may consist of items like operator wages, maintenance expenses, and electricity costs. In cases where operators are needed, the cost of recruiting personnel may be included in fixed costs, especially given the current difficulty in finding qualified operators [3]. This ensures that recruitment expenses are appropriately accounted for in today's tight labor market. It's important to note that the classification of costs as fixed or variable can vary based on the specific context and accounting perspective.

To begin the cost calculation, it is recommended to create a spreadsheet. The first step involves comparing the costs between different automation levels, as illustrated in the example shown in Table 3.3.

Table 3.3: Example of cost comparison per production step with different automation levels

Category	Option 1: Manual	Option 2: Automatic
Cost Overview		
Fixed cost (life span)	€ 20.000	€ 150.000
Variable cost per piece	€ 0,50	€ 0,20
Total cost (life span)	€ 1.020.000	€ 450.000
General		
Life span	10 years	
Annual production volume	200.000 pieces/year	
Break-even Analysis		
Break-even point (pieces)	433.333 pieces	
Break-even point (time)	2,17 years	
Differences		
Absolute difference	€ 570.000	
Relative difference	2,3	

The total cost over the expected lifespan of the production line for each step can be calculated using the formula presented in Equation 3.2. This total cost can then be used to determine the break-even point, both in terms of the number of units produced, as shown in Equation 3.3, and in terms of years, as illustrated in Equation 3.4.

$$TC = FC + (L \times Q \times VC) \tag{3.2}$$

TC	= total cost over entire lifespan of the production line	[€]
FC	= total fixed cost	[€]
Q	= annual quantity produced	[unit/year]
L	= total lifespan of the production line	[years]
VC	= variable cost per unit	[€/unit]

$$BEQ = \frac{FC_2 - FC_1}{VC_1 - VC_2} \tag{3.3}$$

BEQ	= break-even point in quantity	[units]
FC_1	= fixed cost (option 1)	[€]
FC_2	= fixed cost (option 2)	[€]
VC_1	= variable cost/unit (option 1)	[€/unit]
VC_2	= variable cost/unit (option 2)	[€/unit]

$$BEY_{BI} = \frac{BEQ}{Q} \tag{3.4}$$

BEY_{BI}	= break-even point in years, before interest rate	[years]
BEQ	= break-even point in quantity	[units]
Q	= annual production quantity	[units/year]

To account for interest rates, the break-even point in years provided in Equation 3.4 can be recalculated by incorporating the interest rate into the difference in fixed costs between the automation options. This is expressed in Equation 3.5. This approach provides a straightforward way to include the interest rate in the calculation of the break-even point in years.

$$BEY_{AI} = \frac{\frac{(FC_2 - FC_1)\cdot(1+r)^{BEY_{BI}}}{VC_1 - VC_2}}{Q} = BEY_{BI} \cdot (1+r)^{BEY_{BI}} \tag{3.5}$$

BEY_{AI}	= break-even point in years, after interest rate	[years]
r	= interest rate	

This step-by-step comparison of automation scenarios offers valuable insights into the trade-offs associated with the cost of different levels of automation. However, to ensure a thorough and accurate interpretation of the data, it is essential to conduct a cost comparison for all steps across all the scenarios, including the fixed steps. For each step, it's important to determine the fixed cost, variable cost, and total cost over the system's lifespan. This comprehensive data is crucial when integrating all steps into complete automation scenarios.

If all the steps are completed, a comprehensive spreadsheet can be created to display the total cost for each scenario by selecting the corresponding version of the step. As shown in Table 3.4, this can also be applied to analyze fixed costs, by adding up the fixed cost for all the steps per automation scenario, which represents the investment costs.

Table 3.4: Example total cost lifespan comparison across scenarios

TC lifespan	Low	Medium	High	Max rel. diff.	Max abs. diff.
Step 1	€ 756.000	€ 430.000	€ 430.000	1,76	€ 326.000
Step 2	€ 395.000	€ 395.000	€ 200.000	1,98	€ 195.000
Step 3	€ 130.000	€ 130.000	€ 130.000	1,00	-
Step 4	€ 72.000	€ 156.000	€ 156.000	2,17	€ 84.000
Step 5	€ 154.000	€ 154.200	€ 106.000	1,45	€ 48.200
Step 6	€ 431.000	€ 243.000	€ 243.000	1,77	€ 188.000
Step 7	€ 123.000	€ 123.000	€ 96.000	1,28	€ 27.000
Step 8	€ 383.000	€ 292.000	€ 292.000	1,31	€ 91.000
TC lifespan	€ 2.439.000	€ 1.917.000	€ 1.647.000		

Once all necessary data for the cost comparison has been gathered, the next step is the interpretation of the cost overview. The first step involves defining thresholds for key values to assess whether specific steps or scenarios fall within these limits. For instance, set step-specific thresholds that include maximum acceptable break-even points. If a break-even point exceeds this threshold, that automation option may become economically unfeasible. Similarly, compare relative cost differences against predefined acceptable limits. These thresholds are highly context-dependent; a cost difference of €50.000 may be significant in one scenario but negligible when total costs approach €1.000.000. Additionally, differences in aspects deemed less important may not influence decision-making, such as a €10.000 versus €20.000 difference in a step with minimal overall impact.

These thresholds should be defined at both the step and scenario levels. At the scenario level, thresholds might include maximum investment costs. Although highly automated steps with significant investment costs may offer lower total cost over time, they could exceed what a company has available for investing, making lower automation levels a more practical choice for reducing initial capital expenditure.

At the production step-level cost comparison, absolute and relative differences between automation options have already been calculated. Displaying these metrics step-by-step helps identify outliers. Steps with the highest absolute or relative differences highlight the need for further investigation, as they often indicate significant trade-offs or cost drivers. What qualifies as an “outlier” is context-specific and depends on the scale and impact of the costs involved.

Identifying and analyzing these outliers can provide valuable insights. For example, a manual option may seem cheaper over its entire lifespan if the automated alternative requires a costly machine that isn’t recouped. Conversely, an automated step may be significantly cheaper over its lifespan due to reduced labor requirements and lower variable costs.

Once these outliers are analyzed and understood, the findings can be documented as key insights. These insights will then inform Step 5 of the methodology, where cost is compared with other key decision-making factors.

It is important to emphasize that the cost comparison presented here is based on high-level, indicative cost models. The fixed and variable costs per production step are estimated using generalized input values and assumptions appropriate for early-stage evaluation. These models provide a useful approximation of cost trade-offs across different automation levels and scenarios but do not capture all detailed financial factors such as depreciation methods, tax implications, financing costs beyond simple interest adjustments, or complex overhead allocations. As such, the results should be interpreted as preliminary guidance rather than definitive financial analysis. For more accurate and detailed cost assessments, especially in later design phases, companies are advised to develop comprehensive cost models tailored to their specific accounting practices and operational realities.

3.7.3. Quality comparison

When assessing quality in various design scenarios, it is important to focus on two main areas: general aspects, such as transportation, and the specific steps involved in the production process. Evaluating these aspects involves organizing a review session with a key-factor expert on quality to compare and discuss the different design options, as outlined at the beginning of Step 4. During this session, several key points will be addressed. The core focus will be making relative comparisons between the different automation scenarios. How do they score against each other? What is preferred, and what is not, and why? This exploration is essential for creating insights into the quality of the various automation scenarios. An extensive list of questions for the quality review session and the interpretation of the results is provided in Appendix C.1. Example topics include: strengths and weaknesses in quality, trade-offs with other key-factors, meeting minimum quality requirements, design changes for quality (ALARP), feasibility of process steps, comparison of design alternatives, recurring patterns, and adjustments to quality checks for different automation scenarios. After the comparison, the interpretation should determine whether all process steps meet the minimum quality requirements and identify any that are not feasible from a quality perspective. Additionally, the analysis should highlight which design alternatives outperform or under perform others and reveal recurring patterns or necessary adjustments to quality checks across scenarios.

The assessment relies heavily on the insights and expertise of the participants in the review session, rather than on quantitative calculations. Additionally, it can be challenging to determine how quality will be affected at various levels of automation, especially if specific machines or processes have not been defined. As a result, some comparisons may be incomplete or based on assumptions.

3.7.4. Work environment comparison

The next key-factor for reviewing the different automation levels is work environment. As highlighted in Section 2.1.2, the work environment consists of both worker safety and job satisfaction. To compare the work environment across different designs, a review session is conducted for relative assessments. This environment encompasses not only specific workstations but also the broader manufacturing environment, necessitating comparisons at both levels for each automation scenario.

For this comparison, a combination of quantitative assessments, animation and review sessions is employed. The DES model can extract metrics such as minimum, maximum, and average idle times, which provide insights into the proportion of time operators are actively working. Balancing these metrics is crucial: while excessive idle time should be avoided, operators also need enough flexibility for short breaks to maintain their productivity and well-being [87].

Additionally, skill variety, recognized as one of the seven key-factors of job satisfaction, can be quantitatively assessed. An estimation of the required skill variety for operators can be made using a simple table outlining different skills and illustrating how operators may rotate between tasks based on their skill sets. This approach offers valuable insights into the diversity of skills utilized.

During the work environment review session, aspects of job satisfaction such as task identity, autonomy, feedback from the job itself, and interaction with others can be discussed with the help of guiding questions, as stated later in this section. However, two aspects of this: task significance (the degree to which the job has a substantial impact on others) and feedback from agents (the clarity of performance information provided by supervisors or coworkers); are not evaluated at this stage. These factors are highly company-specific and typically do not change with different automation levels, making them less relevant for this phase of the design process.

Ergonomics and safety considerations become more pronounced as detailed designs of machines and workstations are developed. Since such designs may not be finalized for every step at this stage, it can be assumed that each step will meet at least the legal minimum requirements. The focus here is on identifying potential hazards and opportunities for improvement. For example, while adjustable workstations for different operator heights may not yet be specified, they can be noted as an ergonomic requirement. For safety evaluation, different automation designs are assessed based on the literature, the risk estimation matrix for machine safety, and the ergonomic zones discussed in Section2.1.2. An extensive list of questions that can be used in the work environment review session, including question that can guide the interpretation of these results is provided in Appendix C.2. Example topics include:

strengths and weaknesses of automation scenarios, trade-offs with other key-factors, legal compliance, machine safety risks, ergonomic risks, operator autonomy, feedback to operators, and opportunities for collaboration. Additionally, the animation of the dynamic model can help assess the work environment by providing a high-level visualization. It shows how much workers need to walk and how they are distributed throughout the line.

Furthermore, it can be challenging to assess the work environment without valid 3D models for the various automation scenarios. Effective ergonomics often requires visual assessment. Although discrete event simulation models offer some visual capabilities, more detailed 3D models will be necessary in later stages to create specific insights into the work environment. Technologies like augmented reality and virtual reality are particularly valuable in this context, as they enable stakeholders to engage with realistic representations of the workspace and assess ergonomic factors more effectively [52].

3.7.5. Flexibility comparison

When comparing the flexibility of various automation levels, three dimensions are essential: process flexibility, product flexibility, and production volume flexibility, as highlighted in Section 2.1.3. To define these different levels of flexibility, the framework outlined in the same section and summarized in Table 2.2 provides useful guidelines for reviewing flexibility across the different automation levels. The first level refers to systems that allow for flexibility without requiring any modifications. The second level applies to systems that incorporate built-in features to support flexibility, but which require reconfiguration or conversion. The third level characterizes systems that do not possess the capability to be flexible in a particular aspect and must be adapted through the addition of new components or redesign.

Regarding volume flexibility, the DES models of the automation scenarios can offer valuable insights. By conducting experiments that increase the input rate of entities at the start of the production line, it is possible to assess how effectively each automation scenario handles rising production volumes and to identify maximum production capacities that can be accommodated.

To evaluate the different automation scenarios further, several guiding questions for the review session can generate insights. These questions focus on specific production steps and general elements like internal transport. An extensive list of questions for the flexibility review session and the interpretation of this results, is provided in Appendix C.3. Example topics include: process flexibility, product flexibility, production volume flexibility, trade-offs with other key-factors, design changes for flexibility (ALARP), expected flexibility needs, availability of flexibility options, key aspects for ensuring flexibility, comparison of design alternatives, and identification of recurring patterns. The interpretation of the results should determine whether each scenario offers the necessary options for flexibility and identify the key aspects that enable or limit flexibility in different contexts. Additionally, the analysis should reveal which design alternatives perform best or worst in terms of flexibility, along with the reasons for these differences and any recurring patterns across scenarios.

Flexibility heavily depends on context, and a significant challenge arises from the uncertainty about which aspects will require flexibility in advance and in which dimension. If the areas needing flexibility can be identified beforehand, they can be addressed during the system design phase. However, flexibility is often required in response to unforeseen changes, such as alterations in product design or fluctuations in production volume based on market demand. This uncertainty complicates the assessment of whether the system can provide flexibility in the areas ultimately needed. Consequently, this phase of the analysis remains broad and exploratory in nature.

3.8. Step 5. Combining insights of the automation scenarios

The primary goal of this methodology is to provide a clear understanding of the trade-offs associated with different automation scenarios. It serves as a conceptual framework that aids in early stage exploration and helps organize ideas through both data analysis and discussion. While the earlier phases have generated insights and expanded perspectives on production line design, this final step focuses on developing a scenario that addresses weaknesses, eliminates undesirable elements, and incorporates the most advantageous features.

This complete methodology can be executed in two distinct ways, from the start. First, it can follow the traditional waterfall model, where all steps are carried out sequentially, each phase must be fully completed before moving on to the next. This linear approach provides structure and clarity but is less flexible when changes arise later in the process. Alternatively, the methodology can be applied more iteratively: if, during the process, it becomes clear that a particular automation option is not feasible, it can be replaced by a more suitable option in the scenario analysis. This allows for ongoing refinement and adjustment based on new insights, blending the predictability of the waterfall model with the adaptability of iterative development. Such a mixed approach enables teams to systematically progress while also responding to emerging findings, ensuring that only feasible and effective automation options are considered as the methodology evolves.

After reviewing the various automation scenarios based on key-factors in Step 4, the next step is to combine these insights to better understand the trade-offs between key performance indicators. The insights collected vary in scope; some are organized by key-factor across all scenarios, while others are grouped by specific automation scenarios and individual production steps. The data and observations from Step 4 serve as a toolbox that can help clarify these trade-offs. This step involves synthesizing the information at a higher level of abstraction.

To begin, it is advisable to consolidate the data for each key-factor into a comprehensive overview table. This table, as shown in the Example of Table 3.5, can systematically map insights, data points, and relevant observations categorized by key-factor across different automation levels. The table can be filled with data such as the average production volume, using output from the dynamic model; when quantitative values are not available, keywords or small sentences can be used instead. By bringing together the key-factors for each automation scenario or production step, identifying trade-offs between performance dimensions becomes much easier. For example, it was found that in step 2, the option to form the product by hand has a positive work environment. This is because operators can sit together, which enhances connection and ergonomics. However, the production performance is significantly lower in this scenario, with operators producing only 15 units per hour compared to 30 units in the medium scenario. By organizing insights for each key-factor side by side in this structured manner, these trade-offs become apparent.

The table highlights in what way certain automation options are more feasible for production line design than others. Some options may be deemed unfeasible and discarded, while others may stand out as the only viable choices. In some scenarios, multiple options may be closely matched, complicating the decision-making process. Furthermore, the analysis may uncover design improvements that impact all automation scenarios, leading to broader changes.

The overview of key-factors serves as a starting point for iteratively refining the automation scenarios. The aim of this methodology is to provide insights into the trade-offs among different automation options. It acts as a conceptual framework or discussion model to support early stage decision-making by structuring ideas through both data and dialogue.

It is essential to acknowledge that while the current methodology highlights five key-factors, these do not cover all aspects influencing automation decisions. Other crucial elements, such as maintenance requirements, engineering capacity, system integration complexity, and the availability of technical support, also play a significant role in assessing the feasibility and effectiveness of automation solutions. The importance of these factors varies based on context.

Once all relevant data has been collected, attention should focus on the elements that stand out in each scenario. This information can clarify and justify why certain aspects of automation significantly impact the production line. The final step involves synthesizing insights from discussions, modeling, and other data sources to create a scenario that eliminates weaknesses and undesirable steps while integrating the most valuable features. At this stage, it's also important to identify risks associated with varying levels of automation.

This step in the analysis relies on several key assumptions and has inherent limitations that should be considered. First, it assumes that the data and qualitative insights collected in Step 4 are sufficiently detailed and representative to enable meaningful trade-off comparisons. In practice, however, the accuracy and completeness of the information may vary, especially when the data is based on expert judgment or preliminary models rather than empirical validation.

The overview table simplifies complex relationships into a visual format, which, while useful for decision-making, may obscure nuances that require deeper analysis based on all the insights and data created in Step 4. While the overview provides a good summary of the data, it is important to remember that the detailed information from Step 4 can offer a better understanding of the insights. After completing this process, it is advisable to develop a more advanced simulation model to further support and validate the iterative design process. Creating such a model can be challenging; therefore, if the company lacks in-house simulation expertise, involving a simulation expert is highly recommended. Their expertise will be needed for developing and maintaining a robust simulation model to guide future decision-making.

To enhance the decision making process and ensure well rounded scenario development, it can be highly beneficial to organize a dedicated workshop with a multidisciplinary team. In such a workshop, team members collaboratively review the automation scenarios, discuss key-factors, and iteratively refine the design options. One effective method is to use a scoring system, where the team assigns scores to each scenario based on the key-factors, using thresholds or criteria that the team defines together. This approach not only promotes shared understanding and consensus but also helps to identify priorities and potential trade-offs early in the process.

Table 3.5: Example table overview insights key-factors

Level of comparison			Operational performance	Cost	Quality	Work environment	Flexibility
Applicable across all automation levels			Min. required daily production volume = 400	Max investment budget= € 2.500.000	Only one quality check needed at the end of the production.	Connection between operators is important for job satisfaction.	Different products need to be made, but no major changes in volume are expected.
Applicable for entire low automation scenario			Max daily production volume = 350	TC = € 3.900.000 Investment cost = € 1.750.000	Quality is too low because the steps can't guarantee it.	12 operators divided over 8 different types of stations.	Easy to change products/process, but difficult to scale up volume.
Applicable for entire medium automation scenario			Max daily production volume = 400	TC = € 3.750.000 Investment cost = € 2.300.000	Best option, as it uses the human senses, combined with the consistency of the mold.	9 operators divided over 5 different types of stations.	Mold limits product changes, but operators allow some adaptability.
Applicable for entire high automation scenario			Max daily production volume = 450	TC = € 3.240.000 Investment cost = € 2.900.000	Quality is uncertain, as machine damage is not always detected by vision.	4 operators divided over 3 different types of stations.	Can be retooled for new products, but less flexible for frequent product changes.
Step	**Option**	**Applied to scenario**					
1	Combining the raw materials by manually adding them to a machine	Low, Medium High	Warm up period of 3 hours	TC = € 56.000 Investment cost = € 24.000	Quality depends on the quality of the raw materials.	Filling the machine is not very ergonomic because heavy lifting of material.	Machine has the ability to mix many different raw materials.
2	Forming the product by hand	Low	15 products/ h per operator	TC = € 87.000 Investment cost = € 8.000	The manual process is not consistent in quality.	Many operators can sit together, this encourages connection and is ergonomically preferred.	Flexible in terms of process and product. Less scalable for volume.
	Forming the product using mold	Medium	30 products/ h per operator	TC = € 65.000 Investment cost = € 12.000	Combines the operator's delicacy with the consistency of the mold.	Risk of fingers getting stuck in the molds.	Mold limits flexibility; operator use makes scaling harder.
	Forming the product by machine	High	70 products/ h per machine	TC = € 54.000 Investment cost = € 37.000	The machine is less careful and sometimes damages products.	The machine is already on the market and has high safety certifications.	Machine has the ability to change shapes by retooling, can scale up volume when needed.
3	Visual quality check done by operator	Low, Medium	120 products/ h per operator	TC = € 55.000 Investment cost = € 4.000	Operator can better visually inspect than vision.	Performing QC is highly repetitive work.	New checks are easily added for operators; vision systems need reprogramming.
	Automated quality check done with vision	High	140 products/ h per machine	TC = € 42.000 Investment cost = € 35.000		The machine's infeed and outfeed are at an ergonomic height.	

4
Test case Quooker

This chapter demonstrates the methodology designed to analyze trade-offs between automation levels in production line design, as presented in Chapter 3, by applying it to a test case involving the development of a new production line at Quooker. It illustrates the methodology's practical application and validates its effectiveness. The second part of the chapter includes a reflection on the application of the automation evaluation methodology in Section 4.2.

4.1. Test case

The test case of Quooker is excluded out of the public version due to confidentiality reasons.

4.2. Reflection application methodology

The application of the automation evaluation methodology has provided valuable insights into both the method itself and its practical use. In this section, the main findings are summarized, while a discussion follows later. It is important to note that the methodology could be applied in its entirety to the test case, which allowed for a comprehensive evaluation of its strengths and limitations. A schematic overview of the identified strengths and weaknesses of applying the automation evaluation methodology to the Quooker test case is shown in Table 4.1.

Table 4.1: Overview identified strengths and weaknesses after applying the automation evaluation methodology to the Quooker test case

Step	Identified strengths	Identified weaknesses
0	- Five key-factors provided clear structure and guidance	- Very context dependent
1	- Early stage use allowed broad exploration of solutions - Comparing multiple scenarios deepened understanding of automation impact	- Building and updating three models increased workload
2	- Conceptualization phase before modeling improved scenario quality	- Iterative work is challenging for larger changes, as these can significantly alter the scenarios
3	- Deep insights into system behavior - Animation aided communication - Single environment for multiple KPI's	- Very time consuming - Hard to find errors and discuss modeling choices as a single modeler
4	- Combining quantitative and qualitative analysis provides a clear view of automation's impact across the key-factors.	- Difficult quantitative assessment (quality, OEE) - Key-factors expert review sessions reflected only a single viewpoint of the one involved key-factor expert
5	- Overview table aids consolidation	- Final synthesis risked oversimplifying complex findings

A key aspect throughout the application was that the methodology was used in the early stage of production line design. This timing brought both advantages and challenges. On one hand, having many options still open made it possible to explore a wide range of solutions. On the other hand, the lack of clarity in some areas made it difficult to include all relevant factors in the analysis. For example, quantitative assessments of quality and OEE proved difficult at this stage. In the end, only a qualitative assessment was made for quality, and although there was an attempt to quantify OEE, the many assumptions and simplifications led to unrealistic results. Fortunately, certain data was already available at Quooker, such as a detailed cost estimate and a test line from which machine processing times could be obtained. Without this data, gathering the necessary information would have taken much more time, highlighting the importance of early data availability.

The use of the five key-factors throughout the methodology provided a clear structure and guidance for assessing trade-offs between automation levels. This structured approach not only helped to compare scenarios in a consistent way, but also revealed new aspects to consider. Initially, Quooker's focus was mainly on cost and production performance, but the methodology encouraged a broader perspective.

The comparison of three scenarios further contributed to a deeper understanding of the impact of different automation levels at the production line level. While this approach made it easier to see the effects of automation, it also meant that any change or update had to be implemented in all three scenarios. Building and maintaining three models significantly increased the workload. To manage this, the Quooker test case was ultimately carried out using a hybrid approach, combining both waterfall and iterative steps from the automation evaluation method. This allowed for small adjustments to be made fairly easily, but larger changes were often too complex to implement, resulting in some issues remaining in the scenarios even after it became clear they were not feasible.

Another important insight emerged during Step 2, where a conceptualization phase was included before building the dynamic model. This step ensured that the scenarios were well understood and could be refined before moving on to detailed modeling, which improved the overall quality of the models.

Step 3, which involved building the dynamic model and running experiments with it, took much more time to complete than the other steps. Because of this, there was less time left for Steps 4 and 5. The reason Step 3 took so long was the detailed approach chosen for the model. There was a lot of complexity in how humans and machines would work together, which required considerable time to develop. Additionally, three versions of the model needed to be created, which is much more time consuming than making just one. Creating three detailed models is especially difficult when only one person is doing the work. It was hard to discuss modeling choices and find mistakes without another who also worked on the model, and there wasn't enough time to create a fully validated model in the end.

Despite taking a lot of time, this step produced valuable results. The model required careful thought about specific details that hadn't been clearly defined yet, such as whether all operators could work at all stations or if specific skills were needed, how product transportation would work, and what the break times would be. Using animation to present different scenarios to other people in the company was very helpful, as it made the information easy to understand. The model also served as a single environment that offered many insights, including not just the main KPI of production volume, but also resource allocation of operators and machines and the status of input and output buffers at different stations. Running the experiments was relatively simple and provided even more insights. Overall, these factors contributed to a deeper understanding of how different scenarios would behave. However, sharing this knowledge with others who were not involved in the modeling process can be challenging, as the understanding comes from hands on experience with the models and learning about the behaviors firsthand.

In the final step, all insights are consolidated. This synthesis can be challenging because it's difficult to fully capture the depth and breadth of the analysis. With numerous insights gained at different levels, communicating them all clearly can be quite complex. The overview table helps with this process, but since it tries to condense complex findings, some nuance is unavoidably lost in this step. As a result, the summary may become too high level and may not adequately reflect the richness of the insights obtained.

5 Refinement of the methodology trough feedback sessions

In Chapter 3, the final version of the designed methodology is presented. To achieve this version, three feedback sessions were held with groups of participants from different backgrounds who took part in sessions to provide insights on what aspects of the methodology were effective and what needed improvement. This chapter discusses the sessions and illustrates how the earlier versions of the methodology contributed to the development of the final version.

5.1. About the feedback sessions

Goal of the feedback sessions

The design of the automation evaluation methodology presented in Chapter 3 and tested in Chapter 4 is part of a design science approach. A crucial part of this approach is the evaluation of the designed artifact and the iterative improvement of the artifact [30]. The evaluation of the artifact ensures the relevance and effectiveness of the methodology. This was achieved through three feedback sessions with different groups, each providing valuable insights and actionable recommendations. Based on the action points identified in these sessions, targeted improvements were incorporated into the methodology. Each feedback session had general feedback points and specif focus points. The overview of

Table 5.1: Focus points per feedback session

Feedback session	Focus points
General across all sessions	- Clarity and explicitness of methodology steps and assumptions - Alignment with industry practices - Level of detail in guidelines for analysis and comparison - Guidance for interpreting and synthesizing results
1. Automation company	- Strategies for conducting relative comparisons - Approaches for handling and utilizing large volumes of data in decision-making - Methods for summarizing and presenting data
2. Quooker	- Desired insights to be gained from comparisons - Evaluation of the clarity and transparency of each step when the methodology is implemented in practice
3. Thesis committee	- Theoretical alignment of methodology - Check if there are clear connections between steps - Identification of methodology steps that are not made sufficiently explicit

this is given in Table 5.1.

The first feedback session was held with a company specializing in automation technologies and consulting services. Their input focused on the methodology's applicability within the manufacturing industry, offering industry perspectives. The second session involved Quooker, the company that provided the test case for the methodology. Their feedback centered on the practical implementation of the methodology, as they could directly see the results of the methodology applied to the design of their own production line.

The final feedback session took place with the thesis committee at TU Delft, which included two supervisors who are experts in manufacturing. Their academic perspective contributed to a more robust and theoretically grounded methodology. Collectively, these three feedback sessions, each from a distinct viewpoint, resulted in a multi-perspective feedback approach.

It should be noted that there are multiple versions of the methodology. The first version was presented during the initial feedback session with the automation company, and at that time, it had not received any feedback. The incorporation of their feedback led to the development of the second version, which was presented at the second feedback session with Quooker. Following this session, their feedback was incorporated, and the thesis committee provided additional feedback. The integration of this feedback resulted in the final version of the methodology, which is presented in Chapter 3. This chapter will explain the different versions and how feedback has contributed to the development of the final version.

Set up of the feedback sessions
Each feedback session involved a group of participants who did not need to prepare in advance. The sessions included a presentation on the methodology, along with opportunities for immediate feedback on each step of the process. During the presentation, the steps of the methodology were explained in detail and supported with relevant examples, ensuring that participants could easily understand and engage with the material as it was introduced. This interactive approach encouraged direct input and discussion throughout the session.

5.2. Session 1: Automation company

Information feedback session

- *Date*: 15th of May 2025
- *Number of people participating in feedback session*: 5
- *Group of people providing feedback*: employees from a company that sells automation technologies
- *Goal of the feedback session*: to obtain initial feedback on the automation level methodology, specifically exploring its connection with practice of the manufacturing industry.

Overview of the feedback session
The first feedback session was held with an automation company specializing in consulting and selling automation solutions. This provided valuable insights from the perspective of the manufacturing industry, with the primary goal being to assess whether the designed methodology aligned with industry practices. It is important to note that, given their business focus, the participants were likely to favor higher levels of automation, which may have introduced a certain bias into their feedback. The session focused on the initial version of the methodology.

The initial version of the methodology began with identifying automation options and assigning them to different scenarios. Feedback indicated that this step relied heavily on the assumption that the production line process was already fully understood. Without this foundational knowledge, it would be difficult to generate concrete examples of design variations with different levels of automation. As a result, the methodology was updated to explicitly state this assumption before starting the process, ensuring that users are aware of the need for a thorough understanding of their production line. For the remainder of this step, the feedback indicated that the approach was logical and well-received. One positive aspect noted was that it encourages companies to broaden their scope when considering automation options.

The second step of the methodology is about conceptualizing the different scenarios using IDEF0 diagrams and layout maps. The feedback advised ensuring that the conceptual modeling technique used is in line with what the company is already familiar with, as it may not always be IDEF0. Specifically, Material and Information Flow Analysis (MIFA) was recommended as a valuable tool. MIFA helps identify inefficiencies, reduce waste, and optimize production before launching new products or programs. Given its use in manufacturing, MIFA may be a more practical and familiar method than IDEF0 for companies who are already using this modeling technique. After conducting research on this step, it was confirmed that MIFA can indeed be used within manufacturing for process flow conceptualization. While the improved methodology still recommended IDEF0 due to its hierarchical and clear structure, it was emphasized that the choice of conceptualizing technique should align with what the company already uses. If no conceptualizing technique is currently in place, it is recommended to use IDEF0. However, MIFA is also a suitable option, particularly for companies engaged in lean manufacturing, as it is widely utilized within lean practices. The recognition and use of conceptual modeling tools like MIFA confirm that this step is in line with industry practices.

The third step of the methodology involves creating the discrete event simulation (DES) model. Feedback indicated this step is highly valuable because it aligns with tools commonly used to identify bottlenecks and visualize production lines. While the method is based on the theory of constraints, it may not fully resonate with companies that prioritize lean manufacturing and seek to minimize buffers. Nevertheless, the experiments enabled by the model provide significant insights for production line design. No further specific feedback was given on this part, apart from the confirmation that it is in line with industry practices. Therefore, this step required no changes for the second version.

The fourth step is about comparing the different scenarios along the key-factors. For the cost comparison, which focuses on fixed and variable costs per step and per automation scenario, the feedback confirmed alignment with industry practices at the conceptual stage. It was suggested, however, to also include variable costs such as rejection costs. Additionally, a concern was raised about the absence of employee recruitment costs, which is particularly relevant in today's labor market. Therefore, the methodology was updated to recommend that, if a company faces challenges in finding operators, recruitment costs should be included.

For the comparison of more qualitative key-factors: work environment, flexibility, and quality, the original version used assessment sessions where experts scored and assessed the different automation scenarios for the key-factor they specialized in. However, the Quooker test case indicated that this approach sometimes did not provide the desired insights, as experts found it difficult to comparatively assess different automation scenarios in the early stages of production line design. There was also discussion about the theoretical nature of the questions used, which may not resonate with practitioners who favor a hands-on approach. This highlighted the need for more practical, concrete, and relatable questions that offer clear choices and specific examples. In response, the updated version of the methodology includes structured review sessions. These sessions use a set of guiding questions to facilitate meaningful discussions and generate insights for comparing automation scenarios. This approach shifts the focus from simply ranking options to understanding underlying trade-offs trough discussions.

The final step of the methodology in this version was a summarization of the insights created by the key-factors. Since this was not already directly included in the fourth step, the fifth step focused on using insights from the scenarios. However, feedback indicated this step was perceived as lacking clarity and decisiveness. Key questions arose: after collecting extensive data and insights on automation scenarios, what specific actions should be taken with this information? There was debate over whether the methodology generates too much data, leading to a loss of overview, or if it simply lacks clear guidance on how to utilize the data. The main conclusion was that after a broad exploration of scenarios and data, the final two steps should converge to provide more definitive answers. What is the ultimate outcome of the methodology? Should it serve as a basis for discussions about new production line designs, or should it synthesize the strengths and weaknesses of each scenario to develop a best-practice model? This has been addressed by embedding guidance within the steps of the methodology to help interpret the insights generated and determine appropriate next steps. Previously, the methodology concluded with vague suggestions to use the outcomes as "lessons learned." In the revised version, a structured overview table of key-factors has been added, providing a systematic view of each factor and highlighting the trade-offs between them. Additionally, a more detailed section outlines how all insights can be synthesized to support an iterative process that leads to a well-defined and desirable automation design.

5.3. Session 2: Quooker

Information feedback session

- *Date*: 20th of May 2025
- *Number of people participating in feedback session*: 4
- *Group of people providing feedback*: employees from Quooker involved in engineering of production lines
- *Goal of the feedback session*: as Quooker serves as the test case for this methodology, the goal of this feedback session is to ensure that the methodology aligns with the insights needed for the test case and to assess the quality and relevance of those insights.

Overview of the feedback session

The second feedback session was held with Quooker, the company that provided the test case for the methodology. This session focused on the test case and its practicality. As a result, much of their feedback related to the challenges they encounter with the test case. This feedback is crucial, as it helps to determine whether the methodology can offer insights for a company that is in the early stages of designing a production line. Since the feedback session is centered around the test case, the feedback may be somewhat limited to this specific case.

In the version of the methodology presented during this session, there was no explicit preparation step. Quooker's feedback highlighted the importance of defining what should be clear before starting the methodology. Specifically, they recommended that the company's specific goals and operational context must be clarified from the outset. This allows for the early identification of all relevant constraints, requirements, and whishes. Incorporating this feedback, the methodology now includes an additional preparatory step: Step 0, where these elements are explicitly outlined. Furthermore, Quooker advised that the methodology should incorporate elements outside the five key-factors, such as maintenance requirements. As automation increases, so does the need for maintenance personnel, and even at higher automation levels, operators remain necessary for machine supervision roles often filled by maintenance staff who can respond to malfunctions. Also, higher automation levels lead to greater dependency on consistent input materials, product quality, and process reliability. While these aspects are not directly reflected in the five key-factors, they are indirectly addressed under product flexibility and product quality. To address this feedback, the preparation step now includes a section on constraints, requirements, and wishes that should be defined, even if they fall outside the five key-factors.

The first official step involves identifying different ranges of automation for each production step and considering a broad spectrum of automation options. Quooker found this approach valuable, as it encourages companies to look beyond their initial decisions and consider a wider array of possibilities. Typically, companies become locked into certain decisions early on, and this methodology helps counteract that tendency. Additionally, developing automation scenarios alongside the five key-factors was seen as broadening, since Quooker's current practice only considers cost and production performance. Forcing the production line team to consider all key-factors at the outset was viewed as a significant improvement. Since the feedback was purely confirmatory, no refinements were made to this step in the third version of the methodology.

The second step, which focuses on conceptualizing different scenarios, was also positively received. It prompted the design team of the prodcution line to identify early trade-offs between the key-factors. The inclusion of layout visualization in this step was highlighted as beneficial, as it is the first point at which different automation scenarios are made tangible because of the illustrations. Again, since the feedback was confirmatory, no changes were made to this step in the latest version.

For the third step, which involves creating a dynamic model, Quooker's main interests were in the sensitivity analysis and the calculation of OEE. In the presented version, sensitivity analysis was performed for bottleneck machines, but there were no guidelines regarding the appropriate ranges for this analysis. Quooker suggested that the range should reflect the complexity of the machinery involved; more complex machines require a broader range, as their behavior is less predictable. This feedback led to the inclusion of refined guidelines for sensitivity analysis, specifying ranges of +-10% and +-20%, and emphasizing the importance of focusing on complex machines and bottlenecks.

Regarding the OEE calculation, Quooker highlighted the difficulty of accurately estimating the parameters for availability, performance, and quality at the early design stage. They expressed hesitance to provide fixed values for these parameters in the test case, as such estimates are often highly uncertain. To address this, the methodology was updated to include the use of FMEA (Failure Mode and Effects Analysis) and MTBF (Mean Time Between Failures) as tools for making more informed assumptions about the OEE parameters. FMEA provides a structured approach to identifying potential failure modes, their causes, and effects, allowing teams to prioritize issues and estimate the impact on machine downtime. MTBF, on the other hand, offers a statistical basis for estimating average time between failures, which can be used to inform availability calculations. However, even with FMEA and MTBF, it can still be challenging to provide concrete values for parameters. Therefore, an alternative option in the methodology involves using ranges for the different parameters when calculating OEE. By defining upper and lower bounds for unknown parameters (such as failure probabilities, changeover times, or quality percentages), a bandwidth for the OEE outcome can be established. This approach shifts from providing a definitive OEE for each scenario to a risk-driven OEE calculation, which highlights the assumptions or parameter values that may cause performance to fall below minimum requirements.

For the cost comparison in the fourth step, the feedback indicated that this approach closely aligned with Quooker's practices for creating business cases for production lines. They emphasized that key assumptions such as the expected lifespan of the production line and showed production volumes have a significant impact on break-even points, so these assumptions and their effects should be clearly stated. Additionally, when interpreting cost differences, it is important to specify the underlying drivers rather than just distinguishing between fixed and variable costs. The methodology was updated to require that the underlying causes of changes in variable and fixed costs be highlighted, providing clearer insights into what drives cost differences between automation options.

In the fourth step, there was no additional feedback concerning the other key-factors aside from the OEE calculation and the costs that have already been discussed. Currently, Quooker only considers these two factors in their assessment of the production line, which is why their feedback primarily focused on the comparison of these key-factors. However, Quooker emphasized that they found the comprehensive approach of the methodology to be its main added value. In practice, most companies tend to consider only a subset of key-factors and may overlook others. This methodology encourages design teams to address a broader range of considerations early in the process. Additionally, it shifts decision-making from intuition based choices to reasoned, data-driven decisions, providing a structured foundation for justifying those decisions.

5.4. Session 3: TU Delft thesis committee

Information feedback session

- *Date*: 27th of May 2025
- *Number of people participating in feedback session*: 3
- *Group of people providing feedback*: Thesis committee, that consists of two supervisors from TU Delft, with expertise in logistics, modeling, and simulation, as well as the thesis supervisor from Quooker.
- *Goal of the feedback session*: to incorporate academic perspectives in order to develop a more robust and theoretically grounded methodology.

Overview of the feedback session

The final feedback session focused on the third version of the methodology. This version already included improvements based on feedback from earlier sessions with both the automation company and Quooker. As a result, the methodology presented at this session was the most refined to of all the feedback sessions. The thesis committee, therefore, concentrated their feedback on more detailed points, such as making certain aspects more explicit and delving deeper into specific steps.

For the preparation step, the committee emphasized that while its importance was acknowledged, it needed to be more concrete. The version under review offered general recommendations about what should be clarified before starting the methodology, but it did not specify particular items. To address this, the methodology was revised to include a small table outlining possible constraints, requirements, and wishes for each key-factor. Additionally, the original methodology vaguely referred to mapping the production line. This was identified as unclear, so the description was updated to specify that the order and techniques of the production steps should be understood, but that the actual mapping is part of the methodology itself and does not need to be completed at this stage. Another point raised was the absence of a deliverable for this step. Since the preparation can serve as a backbone for the entire methodology, it was decided that this step should be documented and used throughout the process.

The first step of the methodology initially began with identifying automation options based on ranges of cognitive and physical automation. However, the distinction between cognitive and physical levels of automation was not well defined, and it was recognized that multiple tasks within a production step could each have their own range of automation levels. To address this, the methodology was updated with a more explicit explanation of what cognitive and physical levels of automation entail, clarifying that there can be ranges per task and that a production step may consist of multiple tasks. An example was added to further clarify this process. Another feedback point concerned the deliverable for this step. The initial version only mentioned the different automation scenarios, without documenting the trade-offs made in assigning these scenarios. The revised methodology now explicitly includes this documentation as an additional deliverable, ensuring that the rationale behind certain decisions can always be revisited.

In the second step, which involves conceptualizing different scenarios, feedback focused on clarifying what is important to take into account when making the layout maps. The committee noted that this stage should involve rough layout maps, not optimized CAD models, and that the considerations for these layouts should be clearly defined. As a result, the methodology was updated to specify that layout maps should take into account space limitations, walking paths, machine sizes, and transport requirements.

For the third step, which covers the creation and experimentation with dynamic models, the feedback highlighted the need to better define the added value of dynamic models, the variables they provide, and how they compare to static models. An additional section was added to the methodology to explain these points, though a more extensive discussion is reserved for the thesis's discussion and conclusion. The committee also noted that building the dynamic model in the test case was very time-consuming, particularly due to the inclusion of human elements such as task division among operators. This limitation is now acknowledged in the updated methodology, with an explanation of why it is so time-intensive. Furthermore, the verification and validation processes for the model were not well defined in the earlier version. The methodology now includes a more detailed description of specific checks for verification and the use of face validity for validation. Regarding the experiments, the previous version included sensitivity analysis for bottlenecks and volume flexibility but excluded disturbance analysis. The feedback identified disturbance analysis as a valuable tool for assessing the robustness of the production line, so it was added as a recommended experiment. Additionally, the value of model animation was emphasized for providing insights into working conditions and bringing scenarios to life, leading to the inclusion of a section on the insights that animation can provide.

In the fourth step, which deals with cost comparison, the methodology initially did not account for interest rates. The feedback stressed the importance of including interest rates, as they can significantly affect the break-even point in years. The final version of the methodology therefore includes a formula that incorporates interest rates into the cost comparison, building on the calculations already performed.

The final step involves combining insights from the key-factors in a summary table. The earlier version did not specify what should be included in this table. The revised methodology now provides guidelines on the inclusion of quantitative parameters and key words for each factor. One last point of feedback was that the methodology appeared overly linear, whereas a more practical approach would allow for a waterfall process. This has been incorporated by adding a section that allows for immediate application of insights if it becomes clear that a particular automation option is not feasible.

Overall, the feedback session confirmed that the methodology now demonstrates a clear connection between the different steps, is comprehensive, and has been validated through the test case.

5.5. Conclusion of feedback sessions

The feedback sessions with each group have evaluated the entire methodology. As each feedback session led to improvements, the version of the methodology was not the same for each session. Therefore, some feedback given in earlier sessions is not discussed in later ones. It is interesting to see what the main findings of the feedback sessions are and whether they align. As mentioned at the beginning of this chapter, each feedback session had general focus areas as well as specific points relevant to that particular session. This focus was based on the perspectives the group brought and the on beforehand identified weaknesses in the methodology of the presented version, along with suggestions for improvement.

Table 5.2: Main findings feedback sessions

Feedback session	Main findings
1. Automation company	- The use of DES for identifying bottlenecks and the of visualizing production lines is strongly aligned with industry practice - The key-factor review sessions should be more structured - The final step need more clarity
2. Quooker	- Encouraging consideration of a broad range of automation options and all key-factors from the outset is valuable and broadens design perspectives - There should be a preparation step added to clarify operational context - The OEE calculation is challenging in the early-stage, therefore a hard metric
3. Thesis committee	- The preparation step should be made more concrete - The ranges of level of automation on physical and cognitive level should be split instead of combined - The verification and validation of the dynamic model should be better defined - Cost comparison must include interest rate - The methodology is presented as a waterfall model, but there should also be the option for a more iterative approach

The three feedback sessions each provided valuable, yet distinct, perspectives on the automation evaluation methodology. Despite their different backgrounds and priorities, all groups were aligned on several fundamental aspects. They agreed that the added value of the methodology lies in its ability to broaden perspectives on automation levels in production line design, primarily through the structured use of key-factors. This approach encourages consideration of a wider range of automation scenarios and helps teams move beyond traditional or intuitive solutions. Furthermore, there was consensus that combining quantitative and qualitative methods is essential at this early stage of design, as it ensures that both measurable outcomes and expert judgments are systematically incorporated. Clarity, explicitness, and practical applicability in each step of the methodology were universally valued, as was the structured, scenario based approach that facilitates explicit trade-off analysis between automation options. All participants also recognized the importance of adaptability, noting that the methodology should be flexible enough to accommodate company specific practices and constraints.

The differences in feedback were largely shaped by the unique lens of each group. The automation company focused on industry practices and practical modeling tools, advocating for the use of MIFA in conceptual modeling because of its alignment with lean principles. This contrasted with the academic perspective, which pointed out that MIFA's lean orientation does not always align with the theory of constraints that is used in the automation evaluation methodology. Quooker, as the test case company, concentrated on the practical application of the methodology, especially on how to address data uncertainty during early-stage design. Their reluctance to make early estimations led to discussions with the thesis committee, who suggested the use of parameter ranges to manage uncertainty while still encouraging informed estimations. The thesis committee, representing the academic viewpoint, placed emphasis on theoretical alignment and methodological rigor. They highlighted the need for clearer explanations of dynamic modeling and its role in the methodology, as well as the importance of making all steps explicit and transparent to ensure usability for manufacturing companies.

In conclusion, while each feedback session brought its own priorities and critiques, there was strong alignment on the core strengths of the methodology: its structured broadening of perspectives, the integration of qualitative and quantitative insights, and the necessity for clarity and adaptability. The differences observed mainly reflect the practical, case based focus of industry and company users versus the emphasis on theoretical rigor and explicitness from the academic side. This combination of perspectives has contributed to a methodology that is both robust and relevant for early-stage automation decisions in manufacturing.

6 Discussion

In the discussion, the key findings will be summarized and interpreted. Section 6.1 provides a step-by-step discussion of the designed automation evaluation methodology, explaining how each step was developed, analyzing the advantages and disadvantages of each approach and how the designed methodology differentiates from conventional methodologies. In addition it provides an overview of Section 6.2 offers an overall discussion of the added value of the designed automation evaluation methodology, highlights its weak points, the validity of the results and the generalization of the automation evaluation methodology. Finally, Section 6.3 addresses the limitations of the research and provides recommendations for future research directions to further enhance the methodology and its applications.

6.1. Discussion per step of the automation evaluation methodology

Step 0. Preparations before starting the methodology

The preparation step in the methodology is crucial as it establishes a clear starting point for the process. By documenting wishes, requirements, and constraints, a well-defined solution space is created, serving as the foundation for subsequent steps. It is vital to capture all elements at this stage to avoid severe consequences later, such as missed requirements that can invalidate key decisions. This documentation fosters a shared understanding among stakeholders and maintains focus on feasible goals. Additionally, introducing the five key-factors: quality, work environment, flexibility, cost, and production performance, provides a systematic structure, ensuring a comprehensive approach to automation decisions. Although the scope of the key-factors is grounded in literature, it also limits the focus somewhat.

Advantages	- Shared understanding
	- Structured approach (5 kf's)
	- Prevents missing crucial information
	- Strong documented foundation for solution space
Disadvantages	- Other important factors may be overlooked
Differentiators	- Structured approach along the 5 kf's

Step 1. Creating different automation level scenarios of the production line

In the first step of the methodology, the perspective on automation options is broadened by starting from scratch and considering all automation options. This step begins by exploring all possible automation options for each production line step, free from existing solutions or current practices, ensuring no scenario is overlooked and previous decisions do not constrain the team. A key feature is the explicit separation between cognitive and physical automation, encouraging broad thinking about automation tasks. Evaluating both dimensions separately widens the range of potential solutions and prompts innovative combinations that might otherwise be missed. Although the perspective is broad, all options must remain grounded in reality, fitting within the company's feasible ranges.

The evaluation process of assigning the different automation options to the different scenarios is systematic, weighing each possible scenario against the five key-factors to avoid decisions based solely on a single aspect like cost or speed. An expert session is crucial during this step, as specialists from various backgrounds discuss and evaluate automation scenarios in relation to the five factors. This collaboration helps identify early trade-offs between different automation levels. A challenge in this classification of the scenarios into low, medium, or high automation, as boundaries can be unclear and context-dependent. What is medium for one company might be high for another. Careful judgment and open discussions among stakeholders are necessary to classify scenarios appropriately and consider all relevant perspectives.

A significant limitation is that decisions made can have lasting impacts on future evaluations. Illogical or inconsistent choices can distort results throughout the assessment process. Therefore, the methodology recommends iterative revisions and updates. As new information becomes available or inconsistencies are detected, the scenarios should be revisited and adjusted to maintain the validity and relevance of the analysis throughout the process. During the application of the Quooker test case, it became clear that the iterative approach was effective for implementing smaller changes within scenarios. However, when larger changes were required, the process became significantly more challenging, as these adjustments would have altered the scenarios too drastically. As a result, certain elements that had already been identified as unfeasible in earlier stages were still retained in the final scenarios. This highlights a limitation of the iterative method when dealing with substantial modifications, as it can lead to the persistence of impractical options within the scenario analysis.

Advantages	- Fosters innovative thinking while not losing sight of feasibility
	- Considers automation options along the broad view of 5 kf's
Disadvantages	- Mistakes in this step severely impact results
	- Decisions limit adjustments in later steps (major changes too time-costly)
Differentiators	- Distinction between cognitive and physical level of automation
	- Bias is minimized (due to use of 5 kf's)
	- Holistic approach

Step 2. Conceptualizing the different automation level designs
Step 2 focuses on bringing structure and clarity to the development of different automation scenarios. This phase transforms abstract ideas into concrete models, making the options more tangible and manageable for further analysis. By using conceptual modeling techniques such as IDEF0, the flow of processes within each scenario is mapped in detail, which helps to clarify how tasks and information move through the production line. IDEF0 is particularly effective for showing functional relationships and the sequence of operations, allowing designers to visualize the process flow in a structured manner.

However, while IDEF0 diagrams provide a detailed view of the process, they do not always make all differences between scenarios immediately clear. The diagrams focus on the internal logic and connections rather than offering a direct overview of what each automation scenario entails. As a result, layout models are needed to complement the conceptual models. These layout maps give a first impression of how the production line might be physically arranged under different automation levels. They highlight practical considerations such as available space, the integration of hybrid solutions where humans and machines work together, and the organization of transport routes and walking paths. By working through these conceptualization methods, designers are encouraged to actively consider the various levels of automation, their interactions, and the relationships between different production steps. This was also demonstrated in the Quooker case, where this step contributed to further developing the scenarios, ultimately providing a strong foundation for the dynamic model.

Advantages	- Clarifies differences between scenarios
	- Highlights interdependencies of different steps in production line
	- Combines automation scenarios with practical space
	- Strengthens scenarios
Disadvantages	- Conceptualizing multiple scenarios can be time consuming
Differentiators	- Stimulates thinking beyond one automation scenario

Step 3. Developing dynamic models and addressing bottlenecks
The third step in the methodology is the development of a dynamic model. This step is important for finding and addressing bottlenecks. This model allows for experimentation to understand how the system performs under different conditions and to evaluate production performance. A dynamic model captures the changing behavior of a system, unlike a static model. This becomes particularly useful in hybrid automation scenarios where workers and machines collaborate. The processes with operators are more dynamic. Machines are very constant, but operators are not. Processes involving operators are more variable, as operator performance can fluctuate throughout the day, often due to fatigue, which creates a bathtub curve in their activity. Another advantage of the dynamic mode is that, the dynamic model effectively illustrates how various processes interact. Sometimes, processes may not connect seamlessly due to factors such as delays, disturbances, manual transport, or operators being occupied with other tasks. Irregular rework steps also contribute to these issues. The dynamic model can incorporate all of these elements. The dynamic modeling approach provides insights into potential situations within the system, enhancing the understanding of production performance. The model can be improved using the theory of constraints, as it shows the utilization of different resources, making it easy to discover bottlenecks. When a bottleneck is identified, the model can be quickly adjusted, and a new experiment can be run to show improvements and reveal new bottlenecks. This makes applying the theory of constraints very fast and efficient. A downside of this is that you spent time incorporating buffers for theoretical scenarios, while the real scenarios might require other buffer allocations.

One of the key advantages of a dynamic model is that it integrates all dynamic elements into a single framework. There is no need to combine smaller outcomes separately; everything is connected in the large dynamic model, providing answers on different outcomes in just one model. This approach can give insights into production performance such as OEE, daily production volume, sensitivity, bottlenecks, buffer sizes needed, and use of resources. It also gives many insights into the work environment, such as operator idle time, walking distances, interactions between operators, the time and length they are close to each other, and more. The animation feature can show whether operators are running around the production line or if the line is structured.

The animation feature of the dynamic model is crucial for effectively communicating results and scenarios. It visually demonstrates whether operators are efficiently moving around the production line or if the layout is causing unnecessary movement. Additionally, the animation is highly valuable when discussing automation trade-offs and scenarios with stakeholders. This visual and interactive aspect is something that static models cannot provide, making it easier for stakeholders to understand and engage with the results.

Despite all these advantages, a dynamic model has one major disadvantage: it takes a lot of time to model everything correctly. Three different types of dynamic models are needed, and a certain amount of expertise is required if you do not want to spend a lot of time on it. Experts may need to be hired, which can be expensive. In the test case, it was not possible to fully validate the models in the end. This raises the question of how useful the model is in such a case. On the other hand, a simulation with animation can sometimes help validate the model, as the dynamic model provides many values to check if the model is valid at all. If you had only made a spreadsheet model and run it, you might have gotten reasonable numbers for different automation levels, but you would not have seen the same problems that the dynamic model reveals.

Some outputs of the dynamic model can also be generated with simpler models, such as spreadsheets with queuing theory for bottleneck analysis, OEE calculations, and production performance estimates. However, these would not include the dynamic elements just discussed. Additionally, this leads to multiple smaller models that must be manually combined, resulting in a less structured and less insightful approach. If a critical part of the production line is identified and there is interest in more dynamic elements at this part, a smaller dynamic model can be created for that section to provide insights into the dynamic elements. This approach would lead to several smaller models that need to be combined for insights, but the dynamic elements and the bigger overview would be lost, and the combination would need to be done manually. This is a less structured way of working.

The decision to invest in a dynamic model for production system analysis involves a clear trade-off between the additional effort required and the depth of insight gained. While smaller static models can provide certain quantitative results, they inevitably miss two crucial aspects that are essential for a comprehensive understanding of complex production environments. First, static models are unable to account for dynamic behavior. A dynamic model uniquely captures the interplay between machines and human operators, revealing system behaviors that static models simply cannot. This understanding of system behavior becomes much more accessible in a dynamic model, where simulation can vividly illustrate a typical production day. As the model evolves, the modeler gains a deeper understanding by observing how changes in the model affect overall system performance. This leads to the second crucial aspect: the dynamic simulation environment enables a flexible and integrated approach to quantitative analysis of automation scenarios. By consolidating all analyses within a single, comprehensive model, any change made is immediately reflected throughout the system. The flexibility of dynamic modeling allows for the easy incorporation of company-specific elements, as the modeling environment offers numerous options to tailor the simulation to unique operational realities. The animation feature further enhances communication and understanding, making complex interactions tangible for stakeholders. It allows stakeholders to see how operators and machines interact, how workflows unfold, and where inefficiencies or bottlenecks may arise. This visual and interactive aspect is something static models cannot offer, making it much easier for stakeholders to grasp the implications of different scenarios.

Although building a robust dynamic model requires a significant investment of time and expertise, it ultimately proves to be worth the effort. The model delivers a deep understanding of system behavior, offers flexibility for unique scenarios, and provides a holistic perspective that static models cannot match. However, it is important to note that if a dynamic model is to be developed, it should be done thoroughly and professionally to ensure that its full value is realized. Given the resources required to create a dynamic model, and the fact that the outcomes of combining smaller static models are not always clearly defined, it may be worthwhile for future research to explore how these smaller models can efficiently address targeted questions. Comparing their effectiveness and speed with the dynamic model approach could provide valuable insights into when each method is most appropriate.

Advantages	- One simulation environment
	- Allows for experimentation with different conditions & dynamic behavior
	- Identifies bottlenecks between steps in production line
	- Enables easy testing of bottleneck solutions
	- Flexible environment enables customization
	- Facilitates presentation and discussion of results
	- Fosters deeper understanding of system behavior
Disadvantages	- Very time consuming
	- Any modeling errors impact reliability of results
	- Incorporating buffers in the production line might be too early in the process
Differentiators	- One model that provides a lot of data of different 5 kf's
	- Possibility to immediately evaluate solutions to identified bottlenecks
	- Animation fosters deeper understanding of all stakeholders

Step 4. Comparing the different automation level scenarios per key-factor
In the fourth step, the methodology focuses on comparing different automation scenarios using the

five key-factors. The output of the dynamic model serves as a valuable resource for evaluating the main KPI of daily production performance. This approach is already implemented in Step 3, where numerous experiments are conducted to assess and optimize daily output under various conditions. By leveraging the dynamic model, it becomes possible to systematically analyze how different factors influence daily production. An other KPI for production performance is OEE, it is difficult to calculate a precise OEE because many assumptions must be made. The methodology recommends using ranges for input parameters instead of fixed values when data is lacking. This approach helps identify under which conditions the OEE might fall below a critical threshold, turning the analysis into a form of risk assessment that deals with deep uncertainty. Average daily production volume is a more reliable indicator at this stage, as it provides a clearer comparison of how each automation scenario performs under expected conditions.

Cost comparison is straightforward in this methodology. It uses fixed and variable costs, a method confirmed by feedback sessions to be in line with industry practice. This makes it easy to compare different automation options and understand the financial implications for each scenario. The simplicity of this approach allows for quick assessment and supports decision-making without unnecessary complexity. It is important to highlight that this type of cost modeling is purely conceptual in the early stages, as later stages of production line design should take more advanced factors into account, such as cash flow.

The work environment is assessed partly through the animation features of the dynamic model. These animations provide valuable insights into the organization of the production line, such as whether the line is orderly or chaotic, and how workers interact. Idle time and the connections between operators can be visualized, which helps identify potential inefficiencies or safety concerns. However, safety is more difficult to judge at this stage because the machines are not fully developed. The ALARP principle can still be applied to identify areas for improvement, especially regarding ergonomics, even if only at a conceptual level.

Quality is easier to assess because the main flow of the product is already clear in terms of transport and production techniques. Expert sessions can provide useful insights into how different automation scenarios affect quality. The presence of various automation levels reveals where additional quality checks may be necessary, especially when many steps are combined under higher automation. This helps ensure that quality remains consistent across scenarios. As highlighted at the beginning of this discussion, early-stage applications often lead to the challenge of making qualitative comparisons. This difficulty arises from the many assumptions that must be made, which are particularly challenging in the early stages. As a result, the insights gained from the test case are limited to qualitative observations only.

Flexibility is the most challenging factor to evaluate at this early stage. Since the specific machines are not yet fully known, only broad conclusions can be drawn. The methodology allows for general observations about the flexibility of each scenario but does not provide as much depth as for the other key-factors. It may be useful in future work to include additional factors or develop new ways to assess flexibility more thorough.

Qualitative key-factors are explored through expert sessions, which generate valuable insights into how these factors vary across different levels of automation. In the Quooker case, where such sessions were extensively used, it became evident that involving only one expert per key-factor tends to produce insights that are heavily influenced by that expert's individual perspective. This can limit the generalization and robustness of the findings. To obtain more balanced and comprehensive insights, it is advisable to include at least two key-factor experts in each review session. This approach helps to mitigate individual biases and provides a broader range of viewpoints, leading to more reliable and widely applicable conclusions about the impact of automation levels on qualitative key-factors.

Advantages	- Comparisons based on input from various sources
Disadvantages	- Evaluations with many assumptions yield more high-level than detailed insights
Differentiators	- Holistic and structured evaluation of 5 kf's

Step 5. Combining insights of the automation scenarios
In the fifth step, insights from each automation scenario and production step are brought together in a structured table. This overview allows you to see, for every scenario and option, how the key-factors compare directly. The table makes trade-offs between these factors immediately visible, helping decision makers understand the strengths and weaknesses of each scenario at a glance. However, the table can appear oversimplified, as it does not capture all the depth and nuances present in the underlying analysis. The methodology ends quite openly, leaving room for further interpretation. This was also observed in the Quooker case. The table could be made more concrete by introducing a scoring system based on company-defined thresholds. By applying such thresholds, the evaluation becomes more objective and tailored to the organization's specific standards, making the results clearer and more actionable. An alternative approach involves documenting comparisons for each key insight and then collaboratively filling these in during a workshop. This group interpretation can lead to a combined scenario that integrates the best elements from each option. Further research could explore how to move from these insights to one automation scenario.

Advantages	- Easily grasp strengths and weaknesses of automation scenarios at a glance
Disadvantages	- Overview risks oversimplification
Differentiators	- Have a structured overview of trade-offs along the 5 kf's

6.2. General discussion of the automation evaluation methodology

The previous section discussed the designed automation evaluation methodology for specific steps. This section addresses the overarching limitations and requirements that are not linked to any specific steps. It highlights the importance of timing in the evaluation of automation options during production line design. Additionally, it examines the generalization of the designed automation evaluation methodology, which includes the validation process. The first advantage of the designed automation evaluation is that the methodology offers a structured approach for evaluating automation levels in early stage production line design. Its main added value lies in encouraging organizations to take a step back and consider a broad spectrum of automation possibilities before committing to a single direction. This helps break established perspectives and opens up new viewpoints on automation. By systematically examining where different levels of automation are feasible, the method acts as an eye opener, revealing opportunities that might otherwise be overlooked. The method forces organizations to think outside the box. It is designed as a discussion model, moving conceptualization forward and supporting better, more informed dialogues among stakeholders. By making trade-offs explicit and encouraging early stage discussions, the methodology helps teams clarify their priorities and make more balanced decisions.

A distinctive feature of this methodology is its comprehensive focus. Unlike other approaches that can be found in literature as discussed in Section 1.3 that often concentrate on just one or two key-factors, such as cost or operational performance, this method evaluates scenarios across five key-factors: quality, work environment, flexibility, cost, and production performance. These five factors are grounded in academic literature and are commonly used criteria in manufacturing when determining the appropriate level of automation in production line design. This broader perspective ensures that trade-offs between different aspects are visible. For example, two different designs might have similar cost structures, but they could differ significantly in quality or production volume. Standard cost based, or operational performance focused methods would miss these differences, while this methodology brings hem to light, providing deeper insights for decision making.

An other advantage is that the designed methodology offers a holistic approach by considering a wide range of key-factors and incorporating dynamic elements into the analysis. By combining static conceptual models with dynamic models, it captures time-dependent interactions and complexities in manufacturing environments. This allows for identifying bottlenecks, evaluating system behavior under various scenarios, and assessing the impact of changes throughout the production line, resulting in a more realistic understanding of system performance compared to static methods.

Another significant strength is its clear, stepwise structure. It systematically guides users from identifying automation options to scenario development, modeling, simulation, and multi-factor comparison.

By separating cognitive and physical automation and using expert sessions, it broadens perspectives and encourages creative solutions. At the same time, it ensures all options remain practical and tailored to the company's real context and constraints, balancing innovation with feasibility.

Despite these advantages, there are limitations. The focus on five key-factors means that other important considerations, such as maintenance or integration complexity, may be overlooked. Not all key-factors are equally relevant in every context, and their relative importance can shift depending on the specific situation. Effective application also relies on access to detailed data, which is sometimes unavailable, especially in early design phases; missing or unreliable data can undermine the quality of the analysis and limit actionable insights. Additionally, the structured, academically rigorous approach may be perceived as overly complex or theoretical by practitioners. The stepwise process, particularly the development of dynamic models and scenario comparisons, can be time-consuming and require significant expertise, posing challenges for organizations with limited resources or tight project timelines.

The timing of applying the automation evaluation methodology is critical. The early application of the automation evaluation methodology has introduced certain limitations, as some aspects proved too uncertain to estimate. Two clear examples of this are the quality estimations and the OEE calculation. While quality is typically measured using quantitative metrics, in this particular test case it was not possible to demonstrate the impact of different automation levels on quality using such metrics. Instead, only qualitative insights were obtained through expert sessions focused on key quality factors. The dynamic model could have incorporated variables such as rejection rate to illustrate these effects, but this was not done. Instead, the rejection rate was kept constant across all automation scenarios because Quooker preferred not to make speculative estimates in this area. For the OEE, a quantitative analysis was performed using available data from Quooker, supplemented by assumptions and simplifications provided by the engineering team. However, these assumptions and simplifications were so extensive that the resulting analysis was ultimately not valid. During one of the feedback sessions, it was suggested that using parameter ranges could help identify under which conditions OEE might fall below certain thresholds, making the analysis more risk-driven. This experience highlights a key downside of applying the automation evaluation methodology at an early stage of production line design. On one hand, early application encourages discussion and broadens the range of automation options considered, which is a significant advantage. On the other hand, it can be premature to gain meaningful insights into the effects of different automation levels, as many factors remain unclear at this stage.

The generalization of the automation evaluation methodology is a crucial aspect of this discussion. Several factors support generalization. To start with, this methodology is built on a design science approach, which emphasizes the creation of artifacts that solve classes of problems rather than just individual cases. This approach inherently supports generalization by encouraging abstraction and the identification of underlying principles. The ability to generalize the method to other manufacturing companies is significantly enhanced by incorporating input from multiple industry experts during the feedback sessions, which provided diverse perspectives on its broader applicability. Furthermore, the automation evaluation methodology is developed in such a way that every step of the methodology enables customization, making it adaptable to different manufacturing contexts. In addition, the automation evaluation methodology is based on standardized metrics and terminology, leading to the five key-factors: quality, work environment, production performance, cost, and flexibility. These key-factors are widely used to assess automation levels in production line design within manufacturing, ensuring that the foundation of the evaluation methodology is well-known and broadly accepted. Moreover, the validity of the automation evaluation methodology is supported by several factors. The five key-factors are grounded in literature, ensuring a solid theoretical basis. The approach has been refined through multiple feedback sessions with different groups, each providing a unique perspective. Finally, the methodology has been fully applied in a real-world test case, demonstrating its practical relevance and adaptability to actual production line design challenges. And finally, each step of the automation evaluation methodology is comprehensively explained and documented, allowing other companies to adopt and apply it effectively.

6.3. Research limitations and recommendations

The methodology described in this research has several important limitations that should be acknowledged. First, it has only been applied to a single case, making it's tested application highly tailored to the specific company and context in which the thesis was conducted. This creates a risk of bias, as both the development and testing of the method were closely linked to the same organization, which may limit the generalization of the findings to other settings. Another limitation is the theoretical nature of the approach. The methodology is complex and heavily grounded in academic literature, which can make it difficult to apply in practice. This theoretical overload may lead to resistance among practitioners and a lower acceptance rate, especially if the method is perceived as too abstract or not directly relevant to everyday challenges in manufacturing environments. Furthermore, the method is based on five key-factors identified in the literature, but there are other important aspects, such as maintenance and integration complexity, that are not explicitly included. This focus may result in overlooking factors that are critical in practical applications, and it raises the question of whether the selected key-factors always align with the real needs and objectives of companies.

To address these limitations, several recommendations for further research can be proposed. Future studies should explore alternative approaches that offer insights comparable to those of the dynamic model, but without the time-consuming process of building it. By focusing on less complex models, the methodology could potentially deliver results more quickly and with less effort. This could include developing simplified versions of the method for rapid assessments. However, it is essential to compare the quality of outcomes from these simplified approaches to evaluate the trade-off between the time invested and the accuracy or depth of the results. It is also important to test the methodology on additional cases in different companies to assess its broader applicability and to refine the approach based on diverse practical experiences. The inclusion of maintenance as an explicit key-factor should be considered, as this aspect often plays a significant role in automation decisions and may enhance the practical relevance of the method. Finally, further research should be dedicated to developing clear guidance on how to move from the insights generated by the methodology to an iterative and actionable automation design. This would help bridge the gap between conceptual analysis and practical implementation, ensuring that the methodology not only supports decision-making but also drives effective change in production line design.

7 Conclusion

In this chapter, the goal is to draw conclusions based on the insights discussed in the previous chapter. These conclusions directly address the sub-questions presented in Section 7.1 and the main research question outlined in Section 7.2. Section 7.3 presents practical recommendations for companies interested in implementing the methodology, offering guidance for effective adoption in real-world settings.

The goal of this research is to develop an effective methodology for systematically evaluating the trade-offs between different levels of automation during the early design phase of a production line. While existing studies often focus on optimizing individual aspects such as cost or operational performance, this research aims to provide a comprehensive approach that considers multiple key-factors simultaneously. This leads to the following research question:

What is a good methodology for evaluating trade-offs between key-factors of different automation levels in early stage production line design?

In order to answer this main research question, the following sub-questions were formulated:

1. What are the key-factors to consider when evaluating the trade-offs between different automation levels in early stage production line design?
2. What are the key steps in a methodology to provide insights of the trade-offs between key-factors of different levels of automation in early stage production line design?
3. What is the effectiveness of the designed methodology in a practical context to assess trade-offs between automation levels in early stage production line design?

7.1. Sub-conclusions

1. What are the key-factors to consider when evaluating the trade-offs between different automation levels in early stage production line design?
The first sub-question examines the key-factors that should be considered when evaluating trade-offs between different levels of automation in the early stages of production line design. This question is addressed through a literature review in Chapter 2, which identifies five essential factors for understanding the impact of automation levels on production line design. These factors are quality, work environment, flexibility, cost, and production performance.

Quality refers to adherence to design requirements and the quality checks that ensure these requirements are met. The work environment encompasses two main elements: safety (addressing machine safety and ergonomics), and job satisfaction. Flexibility refers to the system's ability to adapt to changes in product design, process, or production volume. Cost includes both fixed costs, such as those for machines, and variable costs, such as labor, capturing the financial implications of various automation choices. Production performance measures the efficiency and throughput of the system, typically using indicators like production volume and overall equipment effectiveness.

These five factors are systematically integrated into the methodology, ensuring that each automation scenario is evaluated based on the key-factors influenced by automation.

2. What are the key steps in a methodology to provide insights of the trade-offs between key-factors of different levels of automation in early stage production line design?
This sub-question addresses the key steps that should be included in the automation evaluation methodology. This sub-question is answered by applying a design science approach, which involves developing, applying, and refining a structured, multi-step methodology specifically designed to address the complexities and uncertainties present at the beginning of production line projects. The answer is established through a combination of a literature review on the key-factors in Chapter 2, a practical case study outlined in Chapter 4, and iterative feedback from both industry experts and academic supervisors, as discussed in Chapter 5.

The methodology begins with a thorough preparation phase, referred to as Step 0, during which all relevant requirements, limitations, and desires for each key-factor are explicitly identified and documented. This step establishes a clear solution space and provides a shared foundation for the entire process. Step 1 involves systematically generating alternative automation scenarios by evaluating feasible options for each production step, taking into account both cognitive and physical aspects of automation. These different automation options are then assigned to low, medium, and high levels of automation scenarios, forming the basis for comparison between the various automation levels. In Step 2, these scenarios are conceptualized using IDEF0 models and layout maps to visualize their structure and interactions, making abstract ideas more concrete and understandable.

Following this conceptualization, Step 3 focuses on developing a dynamic model for each automation scenario to analyze their operational behavior. This step aims to identify bottlenecks and assess system performance under varying conditions. The methodology then moves on to a comparison phase in Step 4, during which each scenario is evaluated across five key-factors: quality, work environment, flexibility, cost, and production performance. This comparison is supported by both quantitative analysis and expert review sessions, ensuring a all-round assessment. Finally, in Step 5, the insights gained from these evaluations are synthesized into a structured overview, using tables, to highlight trade-offs between different automation options and scenarios and guide the iterative refinement of the production line design.

3. What is the effectiveness of the designed methodology in a practical context to assess trade-offs between automation levels in early stage production line design?
To substantiate the effectiveness and value of the designed methodology for assessing trade-offs between automation levels in early-stage production line design, it was thoroughly evaluated through application to a test case and three structured feedback sessions. The methodology was implemented step by step in the real-world context of Quooker, a company facing the challenge of designing a new production line for a new product. This application provided direct evidence of how the methodology offered a clear framework for identifying trade-offs between key-factors, generating and comparing automation scenarios, and visualizing the consequences of different design choices. The use of conceptual models, dynamic simulations, and structured comparisons effectively made trade-offs between quality, working environment, flexibility, cost, and production performance explicit and open for discussion. This process enabled the organization to move beyond intuition-based decisions, systematically applying the five key-factors to gain insights and broaden their perspective.

The three feedback sessions — one with an automation company, one with engineers from Quooker, and one with the thesis committee — provided diverse perspectives on the practical value of the methodology. Feedback from these industry experts explicitly confirmed that the approach is valuable and aligns with industry practices. They highlighted key strengths, including the methodology's ability to broaden perspectives beyond cost and operational performance, its holistic and dynamic nature, and the use of five key-factors that are both relevant and consistent with industry conventions. The sessions also led to improvements, such as clarifying preparatory steps and strengthening the process for synthesizing insights.

However, there are also limitations, which were recognized by the industry experts. The methodology is less effective for estimating operational performance metrics such as OEE in early stages, as limited data makes accurate estimation difficult and often necessitates many assumptions. Its reliance on expert input can introduce bias, particularly when only a small number of perspectives are considered. The focus on five key-factors may overlook other relevant issues, such as maintenance requirements or integration complexity. Additionally, building dynamic models for each scenario can be time-consuming, and the outcomes depend on the quality of the available data. Finally, the structured tables used to summarize trade-offs can risk oversimplifying the complexity of the actual analysis.

In summary, the methodology effectively structures early-stage design, supports comprehensive trade-off analysis, and enables more informed decisions about automation levels by providing a clear, industry aligned framework based on five key-factors. However, its effectiveness is limited when important factors fall outside its defined scope. Another disadvantage is that explicit data may be limited due to the early stage of the design process. Additionally, bias can arise from expert input.

7.2. Main conclusion

The primary aim of the developed methodology is to create valuable insights, stimulate early discussions, and broaden perspectives among stakeholders about the different automation levels in early stage production line design. The methodology achieves this through a clear set of steps:

0. **Preparation:** Documenting the context, requirements, constraints, and production steps to establish a clear solution space and foundation for the methodology.
1. **Scenario creation:** Identifying feasible automation alternatives for each production step, considering both cognitive and physical automation, and developing low, medium, and high automation scenarios for the production line.
2. **Conceptualization:** Developing conceptual models (IDEF0 diagrams) and layout maps for each automation scenario to visualize structure, flow, and spatial arrangement.
3. **Dynamic modeling and experimentation:** Building dynamic models for each scenario, and using these models to analyze system behavior, identify bottlenecks, and conduct experiments (e.g., sensitivity, disturbance, flexibility).
4. **Comparison by key-factor:** Systematically comparing automation scenarios across the five key-factors: quality, work environment, flexibility, cost, and production performance, using both quantitative model outcomes and qualitative expert input.
5. **Synthesis of insights:** Combining findings from all scenarios and key-factors into a structured overview to clarify trade-offs and guide the selection or refinement of the best automation solution.

These steps incorporate three key differentiators compared to existing methods used that are identified through analysis and feedback:

- The holistic and dynamic approach, combining conceptual and dynamic models rather than separate static models, allowing a broader perspective on automation impacts.
- The explicit structuring of trade-offs using five industry-relevant key-factors, ensuring evaluations align with practical concerns beyond intuitive analysis.
- The early involvement of stakeholders, using clear visualizations and structured discussions to stimulate engagement and avoid decisions based solely on intuition.

Application of this methodology in a real-world context at Quooker, together with feedback from industry experts, confirmed that it effectively provides comprehensive, structured, and practical support for evaluating automation scenarios. Although limitations exist, including the need for sufficient data and situations where factors beyond the five key-factors become important, the methodology offers a robust and industry aligned framework that helps organizations systematically explore and compare automation choices in the early design phase.

7.3. Recommendations for practical use of the automation evaluation methodology

For practical use of the automation evaluation methodology, start by gaining a deep understanding of the production process before applying the methodology. In the test case, this foundational knowledge was crucial and enabled a strong start. The core value of the methodology lies in the insights it generates, so it is important to involve as many experts as possible from different backgrounds. This diversity of perspectives helps reduce bias and enriches the analysis. Whenever possible, organize workshops to gather input and facilitate discussion, as these collaborative sessions often lead to more comprehensive and balanced outcome.

The methodology produces a substantial amount of information, therefore document all insights and intermediate decisions immediately as the process unfolds. Doing this prevents loosing track and keeps a clear overview. Keeping a clear record allows you to revisit the rationale behind choices and supports learning for future projects. This practice not only improves transparency but also ensures that valuable knowledge is retained and can be referenced in later stages or by other teams working on similar challenges

It is advised to approach the development of dynamic models with a high standard of quality. If you decide to build a dynamic simulation, ensure it is done thoroughly and professionally. Engaging a consultant or a specialist with extensive experience in factory automation modeling can save significant time and prevent common pitfalls. These professionals often have a wealth of templates and proven approaches, which means you benefit from their years of experience and avoid having to reinvent standard solutions. A well-developed model adds genuine value, providing reliable insights and supporting robust decision-making. If certain aspects are less critical, consider a simplified dynamic analysis or a lighter version of the model, but always match the model's complexity to the decision's importance.

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A

Literature review

Table A.1 provides an overview of the selected literature discussed in Section 1.2.

Table A.1: Literature overview

Title	Author(s)	Year	Reference
A Framework for Successful E-Technology Implementation: Understand, Simplify, Automate	Kapp	1999	[12]
A model for types and levels of human interaction with automation	Parasurama et al.	2000	[13]
Praxis Der Montagetechnik	Konold & Reger	2003	[14]
Assembly automation and product design	G. Boothroyd	2005	[15]
A decision support tool based on QFD and FMEA for the selection of manufacturing automation technologies	Almannai et al.	2008	[16]
Aligning manufacturing strategy and levels of automation: A case study	Lindström & Winroth	2010	[11]
Does Levels of Automation need to be changed in an assembly system? - A case study	Fasth & Stahre	2008	[17]
A cost estimation model for advanced manufacturing systems	Son	1991	[18]
A review of cost estimation models for determining assembly automation level	Salmi et al.	2016	[10]
Design for assembly - The key to design for manufacture	Boothroyd et al.	1987	[19]
Optimal Level of Automation in the Automotive Industry	Gorlach & Wesse	2008	[20]
Enabling flexible manufacturing systems by using level of automation as design parameter	Johanssin et al.	2009	[21]
A Knowledge Based Design Methodology for manufacturing assembly lines	Khan & Day	2002	[22]
A rapid analysis method for production line design	Yoshimura et al.	2006	[23]
Design of collaboration framework for distributed CIM data activities	Kim & Nof	2001	[24]
Hybrid analytic and simulation models for assembly line design and production planning	Hsieh	2002	[25]
Assembly Line Design: Methodology and Applications	Chow	1990	[26]

B

Key-factors

B.1. Guidelines for the levels of severity in safety risk estimation

Guidelines for the levels of severity in safety risk estimation based on ISO/TR 14121-2 (Safety of machinery — Risk assessment) [41].

- Severity levels
  - *Minor*: no injury or slight injury requiring no more than first aid (little or no lost work time)
  - *Moderate*: significant injury or illness requiring more than first aid (able to return to job)
  - *Serious*: severe debilitating injury or illness (able to return to work at some point)
  - *Catastrophic*: death or permanent disabling injury or illness (unable to return to work)
- Probability levels
  - *Remote*: one event each 20 years
  - *Unlikely*: one event each 10 years
  - *Likely*: one event each 5 years
  - *Very likely*: one or more events per year

B.2. Ergonomic zones

Specification of ergonomic zones based on: Ergonomic design principles - Part 1: Terminology and general principles) citeNEN-EN-614-1+A1

1. Green zone
   - Ergonomic principles are fully adhered to.
   - designed for tasks that are frequent or of long duration
   - Ensures maximum comfort and safety, such as tasks performed within the ”zone of comfort reach.”
   - Suitable for essential operations that require sustained use without compromising operator health or well-being.
2. Yellow zone
   - Ergonomic principles are fulfilled, but only to a degree that supports temporary use or short-duration tasks.
3. Red zone
   - Ergonomic principles not fulfilled
   - Conditions, which can lead to unsafe operation

C
Methodology

C.1. Expert review questions quality

The following questions are provided to guide the review session of quality factor:

- What are the strengths and weaknesses of different automation scenarios in terms of quality?
- What trade-offs can be identified between quality and other key-factors?
- Do the current designs meet the minimum quality requirements?
- Are there design changes that could enhance quality without requiring excessive resources (following the ALARP principle)?

After the comparison has been performed, the results can be translated into valuable insights. To guide this process, the following questions can be used to help interpret the comparisons and extract meaningful conclusions.

- Are there any steps in the process that are simply not feasible from a quality perspective?
- Which design alternatives clearly outperform or under perform others in terms of quality, and what are the reasons for these differences?
- What recurring themes or patterns emerge from the comparisons?
- Are any changes to the quality checks necessary for the different automation scenarios?

C.2. Expert review questions work environment

The following questions are provided to guide the review session of the work environment factor:

- What are the strengths and weaknesses of different automation scenarios in terms of work environment?
- What trade-offs can be identified in terms of work environment and other key-factors?
- Do the current designs meet the minimum legal requirements for work environment in the production environment?
- Are there design changes that could create a better work environment without excessive resources (following the ALARP principle)?
- Are there any upcoming regulations that may apply to the specific manufacturing environment? Are new changes expected, and is the production line designed to continue meeting all legal requirements throughout its entire lifespan?
- What risks can be identified in terms of machinery safety?
- How would these risks score on the risk estimation matrix?
- What risks can be identified in terms of ergonomic principles?

- How would the design score across different ergonomic zones?
- Are operators working on a complete and identifiable part of the production process, or only on isolated steps?
- Do different levels of automation result in changes to the autonomy of the operators' tasks?
- Do operators receive immediate and clear feedback on their performance (for example, in terms of output quantity or product quality)?
- How does each automation scenario affect opportunities for interaction or collaboration with others on the production floor?

By integrating the answers to the questions with the skill variety assessments and idle time comparisons, the following questions serve as a guide to interpret the results and draw meaningful conclusions.

- Are there process steps that are not feasible from a work environment perspective?
- Which design alternatives clearly outperform or under perform others in terms of quality, and what are the reasons for these differences?
- What recurring themes or patterns are observed in the comparisons?

C.3. Expert review questions flexibility

The following questions are provided to guide the review session of flexibility factor:

- What are the strengths and weaknesses of different automation scenarios in terms of process flexibility?
- What are the strengths and weaknesses of different automation scenarios in terms of product flexibility?
- What are the strengths and weaknesses of different automation scenarios in terms of production volume?
- What trade-offs can be identified in terms of flexibility and other key-factors?
- Are there design changes that could create a more flexible production line without excessive resources (following the ALARP principle)?
- What type of flexibility do you expect to need for the production line?

Once the comparison is completed, the results from the DES experiment and the findings from the review sessions can be translated into meaningful insights. This process can be guided by questions such as:

- Are the necessary options for flexibility available?
- What are the important aspects identified in the different scenarios to ensure flexibility?
- Which design alternatives clearly outperform or under perform others in terms of flexibility, and what are the reasons for these differences?
- What recurring themes or patterns emerge from the comparisons?