HAN_UNIVERSITY OF APPLIED SCIENCES

Major Project
Flexibility on the improvement of work instruction – an empirical, experimental and simulation

Name of students:	Yuliang Liu (1641491)
HAN Supervisor:	Jannes Slomp
Company:	HAN Lean QRM Center
Company Supervisor:	Frank Vaneker

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PREFACE

For the past few months, I have been working on my thesis, which is the last assignment in my Lean Engineering Masters journey at HAN University of Applied Science. During this time I learned a lot and solved many challenging problems. It is very important that I met many people who helped me during this period, so I want to thank them.

First, I would like to thank my HAN supervisor Jannes Slomp for his help during this period. Jannes always gave me immediate feedback when I asked questions and helped me find the research direction when I was confused. Also, I would like to thank my company supervisor Frank Vaneker. Frank helped me a lot in using simulation software and designing simulation experiments.

Secondly, I would like to thank the companies interviewed in this project and Walraven. They arranged very nice visits and shared useful information for this project. This was of great help to this master project.

While English serves as the main language of this thesis, I sometimes find it challenging to fully express my gratitude in a foreign language. Therefore, I would like to share a sentiment in my native language:

'何德何能，所遇之人皆不偏不倚、传道受业、亦师亦友。'

This expresses my deep appreciation for those who have guided, taught, and befriended me throughout this journey.

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Yuliang Liu

FRONTMATTER

Student: Yuliang Liu
Project title: Flexibility on the improvement of work instruction – an empirical, experimental and simulation
Company: HAN Lean QRM center
Supervisors: Frank Vaneker, Jannes Slomp
Date:13-11-2024

HAN Lean QRM center	HAN university
Frank Vaneker	Jannes Slomp
Arnhem, date :	Arnhem, date :

SUMMARY

In high-variety, low-volume assembly environments, gaps often exist between documented work instructions and actual assembly practices, impacting both efficiency and consistency. When this happens, operators always need to spend a long learning process to become familiar with assembly work, which may result in variations in the same work process even for the same operator, ultimately having a negative impact on work efficiency and failure rate. Consequently, it is crucial to improve the work instruction. However, some companies lack understanding of the role of better work instructions in the improvement of assembly system and how can better work instructions improve the performance of an assembly system. This leads to the research questions: "What are the possibilities to improve the work instructions under the high-variety low-volume environment?" and "How to integrate the improvement of work instructions in improvement activities focused on creating a better output of an assembly system."

To address these questions, a study involved empirical, experimental, and simulation-based methods was conducted. The study aimed to find potential solutions for reducing the gap between work instructions and assembly performance, and to support companies in making decisions with the respect to work instruction improvement in an assembly system. Through observational studies and literature review, the study investigated possible solutions for improving the work instruction. The findings reveal that clearer multimedia format and enhanced visual design can improve the presentation of work instructions. Additionally, focusing on task dependencies, workflow efficiency, and flexibility in sequence design can further improve work instructions, reducing failures and improving assembly performance. Then, experimental and analytical studies were conducted to investigate the importance of variation and its relationship with work instruction. Finally, a simulation study was made based on the above research, using an example of an assembly system in a real company as an illustrative example about why and how to improve the work instruction. The results showed that four methods can be used to improve the simulated assembly system: workload balancing, improving work instructions to reduce variation, professional training, and quality control. Proper sequencing and selection of these approaches based on system differences and cost-benefit balance will have a greater impact on the results. The results also suggest that it is wise for companies to always collect data (failure rates, variations, output quantity, …) to support analysis and simulations.

Key words: work instruction, variation, improvement of work instruction, failure rate, output quantity, simulation, workload balance, professional training, quality control

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ACRONYMS

SME Small and Medium-sized Enterprises
WI Work Instruction
AR Augmented Reality
PDCA Plan-Do-Check-Act

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1 INTRODUCTION

Work instructions in the engineering sector are critical documents that provide detailed, step-by-step guidance on performing specific tasks or operations. These instructions ensure consistency, safety, and quality in engineering processes, helping to mitigate risks and improve efficiency (Jozef & Blaga, 2015). They are essential for maintaining standardization across different teams and projects, ensuring that every engineer and technician adheres to the same procedures and protocols.

In the rapidly evolving field of engineering, the development of work instructions must be both rigorous and flexible. This flexibility allows for quick updates and modifications in response to technological advancements, regulatory changes, or feedback from field operations. Effective work instructions incorporate clear language, visual aids such as diagrams and flowcharts, and are designed to be easily accessible and understandable by all users, regardless of their level of expertise.

The advantages of using effective and flexible work instruction can be reflected in many aspects, such as error reduction, system working efficiency and consistency of the result. Therefore, more and more companies have begun to take flexible work instruction as a research object and make improvements to adapt to the company's main business.

1.1 Background

This project focuses on reducing the gap between instructions and doing the work by means of technological and organizational measures, which is linked with the RAAK project 'flexible work instructions', which is focused on the need to improve work instructions in SMEs'. In SME production/assembly companies (high-variety low-volume environment), often there exists a gap between the work instructions on paper and the actual work operators are doing for the assembly. When this happens, operators always need to spend a long learning process to become familiar with assembly work. This phenomenon may be caused by the complexity or lack of clarity of the work instructions. This may result in variations in the same work process even for the same operator, ultimately having a negative impact on work efficiency. At the same time, inappropriate work instructions can also lead to a decline in product quality. If there is a lack of appropriate quality checks in the work instructions, or if there are no steps to correctly guide operators to conduct quality checks on products, the failure rate in the product production process will increase, and work efficiency will also be affected.

Several companies participating in the RAAK project will be references in this project. Reference will be made to its existing work instruction and its future development. Furthermore, the specific situations of some companies' current production systems will also be referred to, and some analysis and simulations will be performed.

1.2 Problem definition

The current problem is that there is often a gap in SMEs between existing work instructions and actual assembly practices, leading to inefficiencies, process variations, and inconsistent quality in high-variety, low-volume production environments. This inconsistency complicates the learning process of operators and increases the risk of failures. To bridge this gap, a better understanding of the role of better work instructions in the improvement of assembly system and how can better work instructions improve the performance of an assembly system is needed.

1.3 Objective and the research question

1.3.1 Research objective

The main objectives of this project are to achieve the aims:

- To reduce the gap between work instructions and doing the assembly by means of technology and organizational measures.
- To support companies in making decisions with the respect to work instruction improvement for the work to be done in an assembly system.

1.3.2 Research question

The main research question should be:

- *What are the possibilities to improve the work instructions under the high-variety low-volume environment?*
- *How to integrate the improvement of work instructions in improvement activities focused on creating a better output of an assembly system.*

To arrive at answering these questions, it is important to specify several sub-questions to further understand sub-topics. This creates a solid foundation on which conclusions can be built in further stadiums of this research. These topics can be expanded, namely:

- How does the presentation of instructions influence the operators?
- What impact does the logic of sequence in the work instruction have on the performance of assembly activities of operators?
- To what extent will improving work instruction influence the performance of assembly activities of operators?

1.4 Outline of the report

The report will be divided into 8 chapters, they are:

1. Introduction

Shows the background and the research question of the project.

2. Observational studies

Attempts to find references to how companies use and improve work instruction in practice.

3. Literature survey

An extension and further academic research based on the information obtained from observational study, with the aim of finding possibilities for improving work instruction.

4. Methodology

Integrates the methodology used in this master project and determine the research methods for subsequent research.

5. Experimental study

A minor project belonging to this master project, consisting of several rounds of experiments, the purpose is to find the connection between variation and work instruction.

6. Simulation study

A simulation experiment based on an existing assembly system aims to design an improvement plan for the assembly system through PDCA and propose a new plan based on the simulation results.

7. Discussion

Discusses the results and defects obtained in this master project, and propose future research directions and suggestions.

8. Conclusions

States the conclusion of this master project.

The first four chapters will show the background, observational studies, literature research and the methodology to implement the project. This master project will be a step-by-step process and the conclusion of each chapter will be used as part of the research input for the next chapter. The subsequent chapters will show the results of the research and give conclusions to the research.

2 OBSERVATIONAL STUDIES

This section concerns an explorative study in the practice of number of companies. The purpose of the study is to know the current status of companies using work instruction and their views on the future of work instruction improvement.

This section mainly describes the forms and characteristics of work instructions observed in the companies visited, and discusses some of the phenomena. The content of this chapter can lead to some topics in the literature research in the next chapter. The result of the observational study will be used as a reference for the subsequent studies performed in this master project.

2.1 Descriptions of the companies

The descriptions of the company mainly focus on the types of work instructions currently used by the company, how the work instructions are made and future development of the work instruction. The information comes from interviews and discussions with engineers and operators of the interviewed companies. These descriptions help to understand the current status of the use of work instruction in the interviewed companies, and to compare and discuss their similarities and differences. A total of 8 companies were visited in this observational study. The following describes the situation of each company:

Company 1: SME, high-variety low-volume
Company 1 uses paper work instruction mostly. Some of the operators can also get work instructions by scanning a QR-code on the screen near their workstation. The work instruction is expressed mainly in the form of pictures, with a small amount of text added for explanation. In addition, work instructions also include some visual designs, such as using color borders to show the current step in the picture, using arrows and crosses to indicate correct or incorrect operations, etc. During the production of work instructions, engineers will discuss with operators. Operators can also give feedback to the team leader when using the work instructions, and then discuss improvement plans with engineers. The company currently plans to improve the work instruction into a representation only with photos.

Company 2: SME, high-variety low-volume
Company 2 uses digital work instruction. Operators can obtain work instructions in the form of a combination of pictures and text from the digital system of the company. Work instruction consists of pictures and text explanations. The content of work instructions will change according to different departments, and operators in different departments will receive different work instructions even for the same product. Operators can add comments and suggestions to the work instruction as they use it, and the system of the company will submit them to engineers for discussion. It is worth noting that the system currently used by the company was created by lean engineers linked to the ERP system, and can record the time each operator uses work instructions to help with data analysis.

Company 3: SME, high-variety low-volume
Company 3 is somewhat special because it currently has no standard work instruction. Company 3 is very small and has only one operator who performs all assembly work. The operator is familiar with

the products and company 3 has no intention of hiring other operators. Therefore, company 3 currently has no work instruction in use. However, Company 3 currently aims to expand its overseas customer base by developing standardized work instructions that enable customers to assemble the products independently. The new work instruction will be presented in the form of a 3D animation. The starting of the work instruction is a 3D CAD model. The engineers from Company 3 are responsible for arranging the assembly sequence and additional text instructions in the 3D animation. Interestingly, engineers from Company 3 also hope to give work instructions some flexibility when assigning work sequences in order to achieve a dynamic sequencing strategy. Company 3 hopes that the developed 3D animation can be previewed step by step, and each step can be scaled or generated into an exploded view.

Company 4: large company, high-variety high-volume
Company 4 uses digital work instruction. The work instructions are still mainly in the form of a combination of pictures and text, but the difference is that in Company 4, the work instructions also include an exploded view of the product assembly. The reason is that the products of company 4 are heavy-duty transport equipment such as semi-trailers and trailers, which have more assembly steps and require operators to have a more intuitive understanding of the relative positions and connection methods of the components. Also for this reason, Company 4 highly respects task dependency when making work instructions. In addition, similar to Company 3, Company 4 is also committed to developing work instructions presented in 3D animations. Since Company 4 has a large variety of products, this improvement is still under development, but 3D animations of some products are already available for demonstration.

Company 5: large company, high-variety high-volume
Company 5 uses digital work instruction. The biggest difference from the other interviewed companies is that work instructions in Company 5 include a checklist of assembly components. The reason is that in the company, there is a storage of components near each workstation, and this storage contains almost all the assembly components. Operators need to first collect all the components according to the checklist before assembling. The work instruction currently used by Company 5 includes a considerable number of interrelated quality checks. Only after the quality check is completed can the next step of work begin. These quality checks increase the assembly time of the product to a certain extent, but ensure the quality of the product to a certain extent. In addition, Company 5 is the only company that has a work instruction for making work instruction. The reason may be that Company 5 is larger in scale. As a global company, Company 5 tries to make each branch use the same standard work instruction. Implementing a work instruction for creating work instructions ensures that any branch can seamlessly use work instructions developed by other branch teams.

Company 6,7 and 8: SME, high-variety low-volume
Companies 6, 7, and 8 are special. They are sheltered employment facilities, where most of the employees were distanced from the labor market. In these three companies, there was no fixed form of work instruction prepared for the employees. The reason is that in these three companies, in many assembly situations there are a variety of operators, and these operators often have different levels of education and intelligence. On this basis, the companies provide work instructions to operators more

based on individual differences. For example, for some operators who cannot read, the company provides assembly videos or beamer guidance to guide the operators through the assembly work.

2.2 Discussion

For the three companies that act as sheltered employment facilities, because individual differences are so pronounced, it may be important to focus on individual needs when making and improving work instructions. If the diversity of operators is too high, pictures, videos or beamer guidance are better choices than text, but they will have higher costs while achieving higher results. It is also possible for the company to consider whether to provide training to operators who are capable of understanding.

For companies with normal employees, the situation is similar in almost all companies, that is, engineers will interview the opinions of various departments during the process of formulating work instructions, and collect feedback from operators during trial production and improve the work instructions. After the production system is put into production, operators can provide feedback in a timely manner, and engineers will review the feedback regularly, such as once every two weeks or once a month, and discuss possible improvements.

In the process of making work instruction, most of the engineers in the interviewed companies said that they would consider the standards of work instructions based on the individual differences of the operators (such as age, education level, etc.) and the type of company. An engineer from Company 5 said that he would make work instructions based on the lowest level of the operators so that all operators can understand them. Of course, this sometimes brings some problems. For example, operators with higher levels may be unwilling to follow work instructions, resulting in some failures.

In addition, during the interview, engineers from several companies also mentioned the problem of operator variation. The engineers believe that there will be variation when operators use the same work instruction, and even when the same operator uses the work instruction, there will be variation. Improvements to work instructions may be one way to reduce operator errors and variability.

According to the current interviewed companies, it can be found that the variety in work instructions and the way they are developed in different companies are very important. Therefore, the necessity of literature review becomes more important. Literature research can focus on the types and effects of different presentations of work instruction and some logical sequences and strategies in the process of making work instruction.

Also, one point needs to be mentioned, that is, in the exploratory case study, engineers did not seem to consider the overall situation of the "assembly system" or "output" (such as the overall efficiency of the production system, the output quantity, etc.) when improving the work instruction. In subsequent research, some time will be spent trying to focus on this issue, that is, to explore how to integrate the overall goals of the assembly system (such as output efficiency, output) into the improvement of work instructions.

2.3 Conclusion

As a result of the observational study, it can be seen that work instruction varies widely depending on company size, product complexity, and employee characteristics. In companies with a more standardized workforce, the work instruction process is often collaborative, involving input from various departments and incorporating feedback loops during the development and production phases. Engineers regularly improve work instructions to meet operator needs and accommodate process changes.

In addition, some of the companies are trying to improve their work instructions with new technologies, and the purpose is to reduce failure and variation of the operators by promoting a clear understanding of the assembly process. According to the current situation of the interviewed companies, for paper-based work instructions, more pictures instead of text are a better choice. At the same time, visual design can be added to the pictures to reflect important steps. Another possible improvement method is to develop a visual 3D animation, but this improvement needs to consider the cost and operator usage.

When designing work instructions, some companies respect task dependencies and assign task sequences, while others want to add appropriate flexibility to work instructions to achieve dynamic sequencing strategies. These factors will also be part of the final impact on the output of the assembled system.

Overall, those companies are working hard to improve a better work instruction and trying to reduce failures, variation of the operators and improve efficiency through this improvement of work instruction.

3 LITERATURE SURVEY

In this chapter, the existing literature on the research topic is described and critically analyzed. The key aspects of this research are discussed individually within this chapter. The literature research in this chapter will be based on the research questions raised in the first chapter and the observational experimental results in the previous chapter. Its purpose is to find ways to solve the problem in the existing literature. At the same time, some results of the literature survey will serve as reference input for subsequent research.

3.1 Presentation of instructions

The presentation of work instructions plays an important role in determining how effectively users can understand and follow the specified procedures. Effective presentation can significantly enhance comprehension, reduce failures, and improve task performance. Various presentations, such as text, diagrams, videos, and augmented reality (AR), offer different benefits and challenges. In the environment of high-variety low-volume, the text-based instructions are traditional and widely used, but they may not be as engaging or easy to understand as visual aids. This research topic aims to study how different presentations of work instructions will affect the operator's work.

3.1.1 Multimedia presentation formats

Multimedia is a form of communication that integrates various content forms—such as text, audio, images, and video—into a single interactive presentation (Jordan & Packer, 2002). In the engineering field, using multimedia for presenting work instructions can significantly enhance user comprehension and retention. The five main building blocks of multimedia are text, image, audio, video, and animation. Popular examples include video podcasts, audio slideshows, and animated videos. Each multimedia format offers unique advantages and potential drawbacks:

- Text: Text-based instructions are the most traditional and straightforward presentation for work instructions. The advantage lies in the simplicity and ease of production and updating. Text-based instructions require minimal resources to create and can be quickly revised as needed. However, text alone often lacks engagement and may be insufficient for complex tasks that require visual context. Users may struggle with comprehension if the instructions are too long or unclear, leading to failures when using it.
- Images: Images provide a visual representation of the tasks, making it easier for users to understand complex processes at a glance. Diagrams, flowcharts, and step-by-step photos can enhance comprehension by offering immediate visual cues. Research indicates that users often find image-based instructions more intuitive, as they can quickly grasp the necessary steps without reading through a huge amount of text (Nadine, Martin, & John, 1996). However, images cannot describe movement or dynamic processes, which limits the effectiveness for more complex instructions that involve multiple steps.
- Audio: Audio instructions add an auditory element that can guide users through tasks without requiring them to read text or look at images. This can be especially helpful in situations where visual attention must remain focused on the task at hand. The disadvantage of audio instructions is that they typically need to be paired with visual aids to be fully effective, as information by audio alone may not provide sufficient detail or context for complex tasks.

- Videos: Videos combine visual and auditory elements, providing comprehensive, real-time demonstrations of tasks. This presentation is highly effective for illustrating dynamic processes and offering a detailed, step-by-step guide. Videos can show movement in ways that text and images cannot. Studies have shown that videos significantly improve both comprehension and memory of information, as users are more likely to remember visual and auditory cues (Ganier & Vries, 2016). The disadvantage is that it requires too much resources to produce high-quality videos, including time, equipment, and technical expertise. Additionally, videos can be less convenient to reference quickly compared to text or images.
- Animations: Animations offer a dynamic way to simplify complex processes. By breaking down tasks into parts and visually representing each step, animations reduce cognitive load and enhance understanding. They can illustrate movements effectively, making them ideal for showing how different components fit together or operate. However, creating animations requires huge amount of production effort and technical skills. At the same time, there are often some differences between what is expressed through animation and reality. Despite these challenges, the benefits of improved comprehension and reduced failures often justify the investment in animated instructions (Saadé, Nebebe, & Tan, 2007).

A research shows that participants processed pictorial and multimedia instructions more quickly than text instructions and made fewer failures when following multimedia instructions (Irrazabal, Saux, & Burin, 2016). This study considered the presentation (text, images, multimedia) and task complexity (three or five steps). 108 participants read and performed 27 instructions for assembling LEGO TM objects under single-task and dual-task (Participants were asked to perform two tasks simultaneously) (MacPherson, 2018) conditions. The results were judged on the time and failures in the assembly process. Overall, these results support the advantage of multimedia in understanding instructions.

In Chapter 2, observational studies showed that the media presentation of work instruction currently used in most companies is a combination of text and images. This shows that most of the companies have the same understanding about multimedia presentations of work instruction as the research results. Some companies are trying to transform work instructions into 3D animations based on 3D drawings. This shows that with the development of the technology, more companies recognize work instructions in the form of interactive animations and regard it as a future development trend.

3.1.2 Augmented Reality (AR) technique in work instructions

Augmented reality (AR) work instructions enhance real-world tasks by integrating 3D models, images, and documents within the existing environment (Cipresso, Giglioli, Raya, & Riva, 2018). AR technology has visualization, it uses 3D models, holographs, and digital twins to explain complex subjects in a more comprehensible way. Instead of looking at 2D pictures and reading tons of texts, users can explore 3D models from all angles to understand the working process better.

Using AR technology, the work instructions provide step-by-step guidance, highlight key components, and offer real-time data, effectively eliminate failures. This approach improves efficiency, accuracy, and learning experiences across various industries, from manufacturing to maintenance. The most common devices for augmented reality technology are smartphones, tablets, and smart glasses.

The AR technique can be used to replace traditional paper manuals with digital instructions overlaid onto the manufacturing operator's field of view. This integration streamlines operations by minimizing the mental effort required to reference instructions (Mourtzis, Zogopoulos, & Xanthi , 2019). At the same time, using these AR instructions offer manufacturers the agility needed to adapt to swiftly evolving product designs. It can be much faster to edit and distribute the digital instructions through the devices, which ensures that operators have access to the most up-to-date work instructions. In addition, the digital instructions with AR can help to increase the safety of the operators. The instructions will be shown on the working area through the devices, which means that operators do not need to look at the work instructions on paper in work areas that may cause safety hazards (Mourtzis , Zogopoulos , Katagis, & Lagios, 2018).

A classic example exists at Porsche Cars North America, Inc. In 2017, the company announced the launch of "Tech Live Look," an augmented reality technology designed to improve technical service at Porsche in the United States. When a service technician in Los Angeles puts on these special glasses and connects via software to the Porsche technical support team in Atlanta, 2,200 miles away, the support team can see what he sees in real time. This video conferencing-like feature provides instant access to remote experts, allowing both parties to quickly identify and resolve technical issues. This way of exchanging information is much more efficient than sending emails and photos or explaining complex technical issues over the phone.

However, in this observational study, no company has used AR technology to present work instruction, and AR technology is still under development. Therefore, AR technology may be a development form of work instruction presentation in the future, but it will not be mentioned too much in this study.

3.1.3 Visual Design in work instructions

The visual design in work instructions means some elements, for example, layouts, colour, and typography might have influence on the clarity and accessibility of work instructions.

- Layouts: It determines the organization and structure of information, which affects how users navigate and interpret the information. For example, a sequential layout with numbered or bulleted lists can guide the users through the assembly process systematically (Pimminger, Neumayr, Panholzer, Augstein, & Kurschl, 2020). In addition, a standard layout for the company might be important, as it can keep the user from getting confused and make it easier to read the work instructions. Reasonable arrangement of information layout, such as text and pictures, can give users better comparison.
- Colour: The use of colour in work instructions can emphasize key points, and establish visual hierarchy within instructions (Kim & Hyun, 2023). Careful selection of colours can enhance contrast and readability. Users can easily judge different meanings from colours in work instructions, such as using red to indicate precautions. However, it is important to consider colour blindness and ensure adequate contrast between text and background colours to maintain accessibility for all users. Consistent colour coding of different components or steps aids in quick identification and increases user efficiency.
- Typography: It refers to the style, size, and arrangement of text within instructions, impacting legibility and readability. Choosing appropriate fonts and font sizes can enhance

comprehension. Additionally, using bold or italicized text for emphasis can draw attention to critical instructions or safety warnings. For example, enlarge the font size of important matters or erroneous operations (Pimminger, Neumayr, Panholzer, Augstein, & Kurschl, 2020).

- Marks: Marks can also be used when designing the work instructions. A suitable mark with text or picture explanation can better explain the content of work instructions. Another use of marks is to mark errors. Error marks can be used to remind users to pay attention to the places where they often make mistakes.

Optimizing visual design elements in work instructions can significantly enhance their clarity and accessibility, ultimately improving user comprehension and task performance. In the observational studies, it was clearly observed that the engineers who made the work instructions in Company 1 paid more attention to the visual design of the work instructions. The new version of the work instructions used by Company 1 cleverly used colours, shapes and symbols in some photos to replace the text instructions, making the entire work instructions look neater. At the same time, Company 1 was the only one that marked the wrong steps in the work instructions. Although the engineers stated that they were trying to reduce such instructions as much as possible, it cannot be denied that the proper use of visual design can more concisely point out the required information and allow operators to understand more quickly.

3.1.4 Customization and Personalization of the presentation

The customization and personalization involve tailoring the presentation of work instructions to the specific needs, skills, and preferences of individual users. For example, when facing users with higher education or engineering background, 2D drawings or 3D model presentations can be used to customize work instructions because they can understand them. In addition, individual employee preferences and learning styles can also become criteria for customizing work instructions, such as matching the learning styles or experience levels of different operators to improve learning efficiency. Better examples of this topic are those involving people with disabilities. When users exhibit significant reading disabilities, the presentation of work instructions needs to be selected more based on the user's individual circumstances. A study shows that cognitively impaired workers can assemble more complex products up to 3 times faster and with up to 50% less errors by using in-situ instructions (Funk, Mayer, & Schmit, 2015). In this study, to further improve continuous instructions, the researcher built a system that uses in-situ projection and a depth camera to provide context-sensitive instructions compared them to state-of-the-art pictorial instructions in a user study with 15 cognitively impaired workers. The results of the user study suggest that in-situ instructions have several advantages over the state-of-the-art pictorial instructions. First, the time per brick is up to 1.6 times lower using the in-situ instructions. The difference between the in- situ and pictorial instructions is statistically significant for all used complexity levels that were used in the study. Second, the errors per brick is up to 3 times lower using the in-situ instructions compared to pictorial instructions.

Another study which belongs to this master project showed that giving operators the opportunity to participate in the creation of work instructions when implementing personalized work instructions may have a positive impact on work efficiency (Liu, 2024). In order to properly understand the impact of user-created instructions, the study designed two experiments with a total of two rounds of testing.

In Experiment 1, participants were asked to create work instructions by themselves and complete more assembly times when only given a product overview (photos of building blocks) as a reference. In Experiment 2, participants were asked to assemble using the work instructions created by participants in Experiment 1 as a reference. Comparing the time data and learning curves obtained in the two experiments, it can be concluded that the implementation of user-created instructions may improve work efficiency, but it has individual differences. Specific individual differences are reflected in the form and logic of work instructions and personal knowledge and ability levels.

3.2 Logic of sequence

The logic of sequence refers to the structured order in which tasks or steps are arranged in work instructions. This sequencing is important for ensuring that tasks are performed efficiently and correctly, minimizing errors and enhancing productivity. A well-designed sequence considers task dependencies, prioritizing steps based on their logical and functional relationships. By optimizing the order of operations, the logic of sequence helps to simplify workflows, reduce cognitive load, and facilitate better understanding and execution of complex procedures. Additionally, it can accommodate flexibility, allowing for variations when needed while maintaining overall process coherence and effectiveness.

Optimizing work sequencing in flexible instructions is an important aspect of workflow management that aims to enhance efficiency, accuracy, and adaptability in various operational settings. The main objective is to determine the most effective order for tasks to be performed, ensuring that each step logically follows the previous one while allowing room for adjustments based on real-time conditions. A very important thing is to first clarify the important factors that determine the order before considering optimizing the order in the work instruction. According to literature research, some of the important factors are:

- Task Dependencies
- Workflow Efficiency
- Flexibility/dynamic sequencing strategies
- Human Factors

3.2.1 Task dependencies

Sometimes there are dependencies between different tasks, and some steps often require other steps to be completed before assembly can begin. For example, when assembling a coffee machine, the outer shell needs to be assembled after other internal parts are assembled. Similar to the dependencies in project management, the dependencies of tasks in industrial assembly production can also be divided into four types:

- Finish-to-Start (FS): The most common type where a successor task cannot start until its predecessor task finishes. The previous example related to the coffee machine belongs to this kind of task dependency.
- Finish-to-Finish (FF): Two tasks must finish at the same time. For example, before starting the next stage of assembly, the quality of the previous assembly steps needs to be checked.

- Start-to-Start (SS): Two tasks can start simultaneously, but one depends on the other to start. For example, when testing the working efficiency of a device, the working efficiency test can be started only after the device starts working.
- Start-to-Finish (SF): One task must start to allow another to finish. This dependency is rare.

(Institute, Practice Standard for Scheduling, 2011)

Clearly defining dependencies in work instructions ensures that tasks are performed in the correct order, reducing errors and rework. It helps in optimizing workflow by aligning resources effectively. It also helps operators understand the logical sequence of tasks and their interdependencies.

There are some tools which can visualize task dependencies and ensuring the correct sequence of operations in work instructions, for example, sequence diagrams and Gantt chart. A sequence diagram helps illustrate the interactions between different tasks, highlighting the order in which they should be executed and the dependencies between them. Sequence diagram is mostly used in the area of software engineering. A Gantt chart is a project management tool used to illustrate the relationship between work completed over a period and the planned work time. A Gantt chart can include task start and end dates, milestones, dependencies between tasks, assignees, and more (Institute, Guide To The Project Management Body Of Knowledge PMBOK Guide, 2021). Although used in different domains, both tools express task dependencies in terms of sequence and time. However, since these tools can only be used in concept for optimizing work sequencing in work instruction, they will not be explained in detail.

3.2.2 Workflow efficiency

The focus on workflow efficiency means simplify tasks to reduce unnecessary steps and arrange the excess workload reasonably. This can help to enhance workflow efficiency and balance the bottleneck in the process. This involves analyzing the entire process and eliminating any bottlenecks or redundancies. Such optimization requires sufficient understanding of the entire assembly process and data analysis of each step in the work instruction. It is suitable for improving work instructions that have been used for a period (Kougka, Gounaris, & Simitsis , 2018) (Do, et al., 2021). For instance, in an assembly line for electronic devices, detailed work instructions may initially include redundant checks and rechecks of components. By analyzing the necessity and effectiveness of these checks, manufacturers can identify and eliminate unnecessary steps, thus speeding up the process without compromising quality. This approach not only makes the workflow more efficient but also reduces the cognitive load on operators, allowing them to focus on essential tasks.

Efficient workflow also involves the strategic arrangement of workloads to prevent bottlenecks. Bottlenecks occur when one part of the process slows down the entire operation, often due to imbalanced task distribution or inefficiencies in a specific area (Germs & Riezebos, 2010). To address this, it is crucial to analyze the workflow and identify stages where bottlenecks are likely to occur. Balancing the workload involves redistributing tasks to ensure that no single workstation or operator is overwhelmed. For example, if one stage of the assembly process consistently takes longer than others, tasks can be reassigned or additional resources can be allocated to that stage. This ensures a smoother flow of operations and prevents delays that can impact overall production timelines.

Improvements to workflow efficiency in work instruction could adopt approaches suggested in observational studies, such as listening to feedback from operators directly involved in the process, or using digital work instructions and technological advances such as real-time updates can further streamline operations and ensure instructions are always up to date.

3.2.3 Flexibility/dynamic sequencing strategies

Same with task dependencies, it is also common that the jobs in the work instruction sometimes do not have any sequence constraints. At this time, the work instruction presents flexibility, that is, the operators may need to adjust the order of tasks according to real-time conditions, such as material loss during cutting and assembly, and different workstations required for different operations. Dynamic sequencing strategies involve the real-time adjustment of task order and priorities based on current conditions and constraints. This approach can significantly enhance workflow efficiency, especially in complex and variable environments (Gong, et al., 2024) (TANIMIZU, ISHII, & YOKOTANI, 2014). This approach can also be considered in the process of improving work instructions. The improvement steps of work instructions can be flexibly adjusted, which may improve the overall improvement level.

A well-known example in real life is the Toyota Production System (TPS). Dynamic sequencing within the TPS involves the real-time adjustment of task order and priorities based on current conditions. TPS incorporates real-time data collection through IoT devices and sensors that monitor the status of machines, inventory levels, and production rates. For example, if a machine sensor detects a potential issue, the production schedule is dynamically adjusted to allocate resources to maintenance or switch tasks to other machines. If such concepts and steps can be added to the work instruction, such as asking operators to regularly check the status of assembly equipment or productivity data, it can better help adjust some flexible steps in the work instruction (Toyota Production System, n.d.).

3.2.4 Human factors

The approach of human-centric recognizes that human factors, such as cognitive load, physical strain, and overall job satisfaction, significantly impact efficiency, productivity, and product quality. By creating work instructions that are tailored to human abilities and limitations, manufacturers can enhance performance and create a more positive working environment. (Boy, 2017). At the same time, specific factors of the operators, such as left-handedness, personal background, and other factors similar to personalization, can also be taken into account here. Key considerations of human factors and ergonomics include:

- Cognitive Load: Simplifying instructions to reduce mental effort. Instructions should be clear, concise, and easy to follow, using visual aids where possible.
- Physical Ergonomics: Designing tasks to minimize physical strain and prevent injuries. This includes considering the height of workstations, the weight of tools, and the need for repetitive motions.
- Psychological Factors: Ensuring that work instructions contribute to job satisfaction and motivation. This involves recognizing achievements, providing feedback, and fostering a sense of accomplishment.

When designing the logic of sequence in work instructions, human factors are taken into consideration, which is more reflected in making it easier for operators to understand the meaning of the logic arrangement and arranging appropriate logic according to the operator's physical condition (such as left-handedness, etc.). This is the same as part of the concept in customization and personalization. Therefore, these two parts can be discussed and considered together.

3.3 Impact of work instructions on production variability and efficiency

In manufacturing environments, different factors, such as cycle time variability, operator skills, and adherence to work instruction, will influence overall production outcomes a lot. Work instructions establish standardized procedures that specify how tasks should be performed at different stages of production. This standardization is intended to minimize variation by ensuring consistency in methods and results. However, the degree of standardization must be balanced with the need for adaptability to accommodate changes in production requirements, equipment capabilities, and environmental conditions. An obvious example is that when using the same work instructions, operators will have variations in work efficiency due to personal circumstances. Even the same operator performing the same task will produce variation. These differences can sometimes lead to very different results in the entire production process Therefore, it is necessary to ensure the clarity and consistency of work instructions to reduce differences in operators' understanding. After improving the work instructions for this situation, it may be possible to add corresponding professional training to further expand the effect. Such improvements may also have an impact on the average processing time of assembly work to some extent. There is no strong literature to prove the point of view on this topic, but there are some theories and methods that can help develop research in this area, such as Kingman's equation. Analytical study can be done by calculating with Kingman’s equation.

3.4 Conclusion

This chapter mainly studies the methods to improve work instruction from the perspectives of presentation and logic of sequence. From the perspective of presentation of work instruction, a more achievable and simpler approach is to consider clearer multimedia formats. At the same time, visual design can be added to explanatory images and text to emphasize key points and avoid failures of operators. For companies with sufficient costs, they can also consider developing work instructions using 3D animation as presentation.

Logic of sequence emphasizes that some rules can be followed when creating and improving work instructions, such as task dependencies and workflow efficiency. Paying attention to task dependencies when ordering the steps in a work instruction can help users understand the logic of the steps more easily. Workflow efficiency, on the other hand, may require the company to collect data on a work instruction that has already been put into use. Eliminating redundant steps and balancing workloads would be of great discussion value. In addition, flexibility can also be considered in terms of sequence to respond to situations that may arise during the production and assembly process.

The variation exhibited by operators when using work instructions is a topic worthy of discussion and experimentation. Since there is no good literature as a reference, analytical study based on Kingman's equation and more experiments/simulations can be designed to gain insights in this regard. At the same time, due to the adjustment of the steps in the work instruction, it may have an invisible positive impact on the quality of the product. These experiments and simulations will be presented in subsequent chapters.

4 METHODOLOGY

This chapter concerns the methodology used in this master project. The methodology will be discussed starting with the observational study, and the method used in each step and the possible results will be briefly described. This discussion will help to develop the final goal of the study, which is to develop a methodology that companies can use to incrementally improve work instructions and that can be supported by data.

4.1 Conceptual model

Before discussing the specific methodology, a conceptual model will be presented based on the purpose and research content of this master project. This conceptual model will serve as research input for several steps in the methodology, helping these steps to determine the objectives of the research. The conceptual model is shown in the figure below:

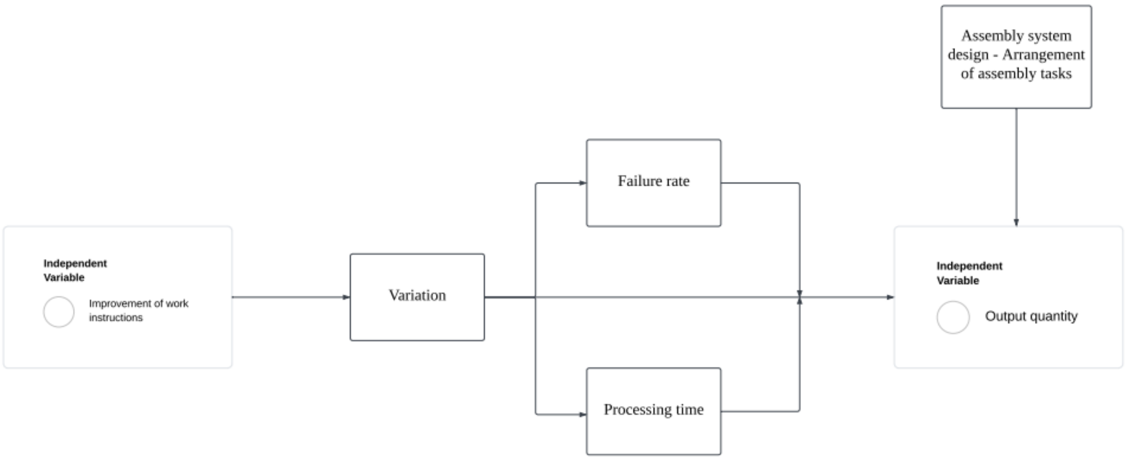

Figure 1, Conceptual Model

This conceptual model explores the impact of improved work instructions on production output by studying how they affect key factors in the production process. The core is to position the improvement of work instructions as an independent variable that helps to reduce the variation in operations, which lead to impact on failure rate and processing time. The output quantity of the system, or the performance of the system, is the criterion for measuring whether the independent variables are effective. At the same time, reduction of variation also has a direct impact on the output quantity. In addition to this part, as mentioned in the previous observational study and literature survey, assembly system design - arrangement of assembly tasks also play a role in the study. These factors will jointly affect the output quantity of the assembly system. In the methodology and subsequent research, this conceptual model will be followed, but some factors may be slightly changed depending on the specific content of the research.

4.2 Description of methodology

In this study, the research steps will be divided into 5 steps according to the research process. The content and results of the steps can be expressed and explained using a flowchart. The flow chart of the method is as follows:

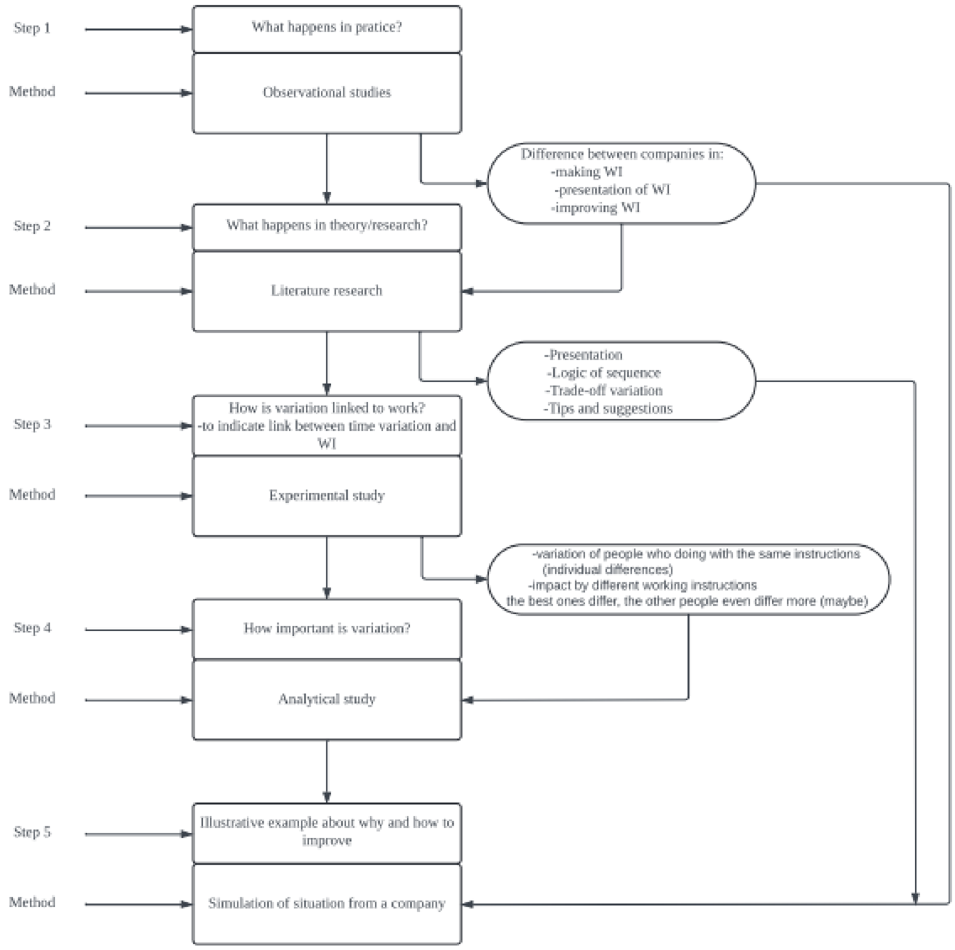

Figure 2, Methodology

Depending on the content of the research, the method will be divided into five steps. Each step starts with a problem or a problem that wished to be solved through the method, and uses the relevant method to get the result. The results obtained in some steps may be used as input for the method in the subsequent steps.

- Step 1. What happens in practices?

The method used for solving the step 1 is observational study, which is presented in chapter 2. The observational study mainly involves visiting several companies in the RAAK project, observing the work instructions in the companies and talking to some engineers. It shows variation in practice, and the need to gain knowledge with respect to best practices and future opportunities to improve the work instructions

The output of this step is the differences in work instructions within the company, as the way of making work instructions, presentation of work instructions and the way of improving work instructions. This information will serve as the basis for the next step of research, which is to help determine the focus and content of the research in the literature research.

- Step 2. What happens in theory/research?

The second step concerns the literature review in chapter 3. The focus is on relevant literature research on topics related to the observational study and the questions raised in Chapter 1. The results of the study are presented in Chapter 3 and will serve as reference input for experimental studies and simulations in subsequent steps. In addition, the findings can provide recommendations on how companies can improve work instruction.

- Step 3. How is variation linked to work?

In step 3, the relationship between time variation and work instruction in the production process will be studied by means of an experimental study. An early research belongs to this master project will be further studied to find out the extent of time variation in this study and the possible relationship between time variation and work instruction. The experiment was divided into two rounds. In the first round, participants were asked to make work instructions using any reference and presentation according to their own preferences during the product assembly process. In the second round, participants were asked to assemble the same product following the work instructions selected in the first round. The results can be obtained by analysing the time performance of each participant in the experiment when making and using work instructions.

The results obtained in step 3 will be more complicated. First, the time variation produced when different participants use the same work instruction will be studied (individual difference). Then, the effects of different work instructions will be discussed, for example, by comparing the variation among participants who used the least time when using different work instructions, to explain whether different work instructions are a factor causing the variation.

The study shows different types of variability:

(i) The variability in time that a worker needs when using the same instruction for subsequent products.

(ii) The variability in time needed by different workers using the same work instruction

(iii) The variability in time needed in case of different work instructions for the same product.

This information is relevant when searching for improvement options of the work instructions.

- Step 4. How important is variation?

In step 4, analytical study will be done. The analytical study will be based on Kingman’s equation. A simple computational experiment will be designed to obtain the effect of improving the work instruction based on Kingman's equation. The experiment is based on a simple single-workstation system. This experiment will design the system's utilization, processing time, and variation, and compare the waiting time in queue as the output. The purpose of step 4 is to preliminarily explore the impact that variation may have on the system and obtain a more reliable basis through calculation.

Due to space constraints, and there are some flaws in this study, the analytical study will be presented in Appendix A and a brief introduction of the results will be given at the beginning of the next step.

- Step 5. Illustrative example about why and how to improve

Step 5 is a more realistic extension of the study in step 4. In this step, a real-life assembly system is modelled and studied to find and discuss improvement. An important difference is that the dependent variable in step 5 (output per time unit) is different from the output in step 4 (waiting time before the station). The reason is that it shifts focus from a simplified model (step 4) to a more comprehensive and realistic assembly system. In step 4, the dependent variable, waiting time, is a useful metric for studying how variation affects individual workstation performance and queuing. In step 5, modelling a real-life assembly system requires considering the entire production flow and assessing the overall efficiency of the system. Therefore, “output per time unit” becomes the more meaningful dependent variable, as it directly measures the assembly system’s productivity and efficiency, which better reflects real-world goals. The results will show how better work instructions can be achieved in the context of assembly system improvements.

In the simulation experiments of step 5, quantitative experiments will be used to collect the data obtained in the simulation. The simulation experiment will start with an illustrative example of a production line to establish a basic understanding of the system's behaviour. Building on this, more simulations of different situations will be made for a realistic exploration of potential improvements. As will be made clear, the improvement of the work instructions may have an important role, under certain conditions which will be discovered in the simulation study. After the simulation studies, an attempt will be made to propose a step-by-step method to improve the system output, including work instructions.

4.3 Conclusion

In conclusion, this master project uses a multi-method approach, combining observational, literature, experimental, analytical, and simulation studies to address the research questions across five structured steps. Each method builds on insights from previous steps, creating a cumulative framework to explore work instruction improvement and the impact of variation on production performance. Beginning with real-world observations and theoretical foundations, this study then moves toward experimental validation and simulation, offering practical solutions for improving work instruction design and system productivity. This integrated methodology aims to yield good recommendations for improving the assembly system.

5 EXPERIMENTAL STUDY

In this chapter, an experimental study will be conducted and discussed. The early research belongs to this master project mentioned in the literature survey and methodology can serve as reference for experimental design. Analysis of the experimental data obtained in this study can lead to conclusions about how variation is linked to the quality of work instructions. This conclusion can be used as input for simulation experiment design.

5.1 Introduction of the experiments

The study concerns two experiments with a total of two rounds of testing:
In Experiment 1, eight participants were tasked with producing eight products based on provided visual references. During the assembly of the initial product, participants were required to create their own work instructions. Following the completion of the first product, participants were given an opportunity to refine and improve their initial instructions. Subsequently, they were asked to follow the work instructions they made to complete the assembly of the remaining products. The data used for comparison is the time it took participants to complete the assembly of each product in Experiment 1. In addition, there is a special rule that every time the participant needs to use a part of a different colour, they need to mark it on the table. This special rule is intended to make participants spend more time when using parts of different colours, so that they will think more about the logical sequence when making work instructions. The purpose of Experiment 1 was to find individual differences among participants in making individual work instructions. At the same time, the logic and preferences used by participants when making their own work instructions will be used as the basis for selecting sample work instructions in Experiment 2.

Figure 3, Product of Experiment 1

Experiment 2 involved seven participants who completed two rounds of production, each consisting of eight products. These participants were instructed to follow three different work instructions derived from Experiment 1 while assembling the products. The instructions were selected based on their perceived effectiveness or logic. The time data obtained in Experiment 2 were used to analyse the variation of the same participant when using the work instruction and the variation of different participants when using the same work instruction.

To find the variation caused by work instructions and personal factors during the same assembly process, the data obtained in Experiment 2 will be focused on and conducted for further analysis. In Experiment 2, 3 of the work instructions made by students in Experiment 1 were selected for testing. They are:

WI 1: The main assembly logic is to assemble parts of the same colour first. The creator of this WI wanted to save as much time as possible by using parts of different colours. The work instruction is presented in the form of slides. Different shapes are used to represent different parts, and there are quantity markings.

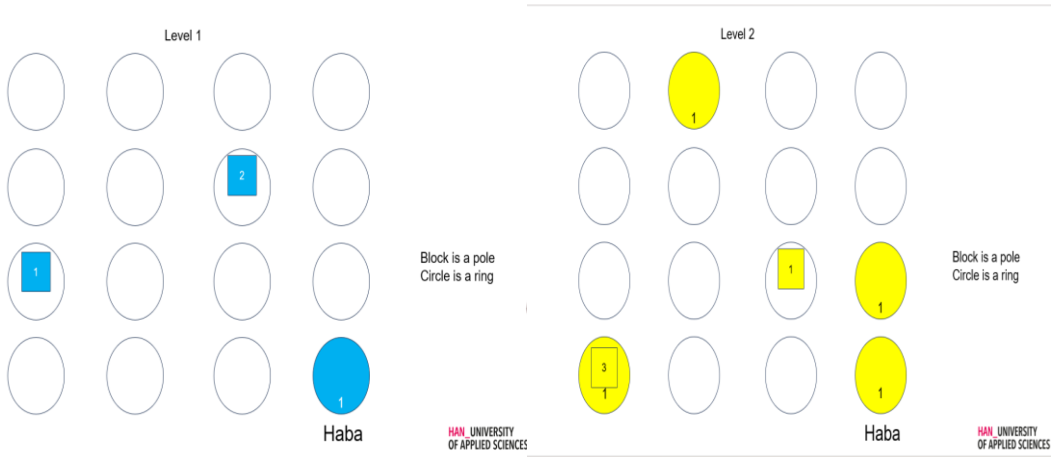

Figure 4, WI 1 in Experiment 2

WI 2: The main assembly logic is to assemble from the bottom to the top. The creator of this WI wanted to assemble the product layer by layer like building a wall. The work instruction is presented in the form of slides and explanation text.

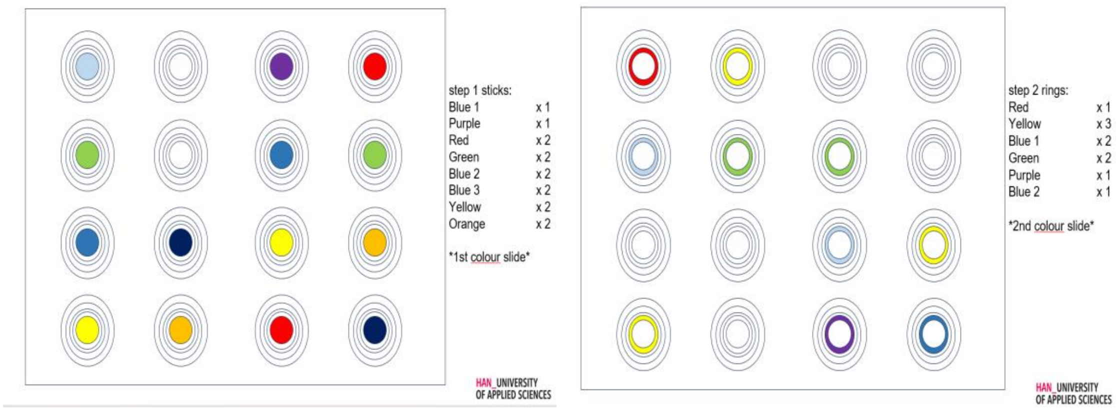

Figure 5, WI 2 in Experiment 2

WI 3: The main assembly logic is to assemble from left to right. What's interesting is that the creator of this WI gave priority to assembling columnar parts, but this may bring risks, such as the lack of fixation of the completed parts leading to collapse. Another difference from the previous two WIs is that this WI is presented in the form of photos.

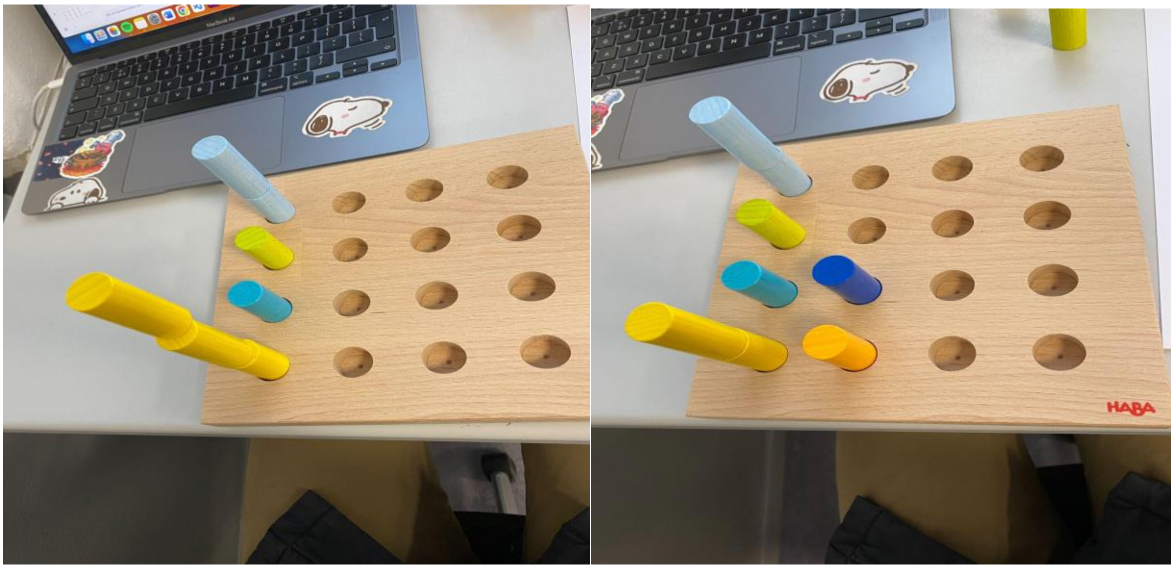

Figure 6, WI 3 in Experiment 2

According to the analysis and results of the research, the work efficiency is the highest when participants use work instructions 3. Therefore, the variation analysis of the performance of participants when using work instruction 3 will be first carried out. The goal of the analysis is to find to what extent(percentage) the variation will be in the simulation.

5.2 Variation with good work instruction

As mentioned earlier, participants performed best when using work instruction 3, so it was considered the better work instruction under the same circumstances and will be studied first based on it.

5.2.1 Individual variation analysis

First, the variation of the time taken by the seven participants to perform eight assembly tasks using work instruction 3 will be calculated. The calculation will be performed using Excel and expressed in the form of table and chart. The participants' overall performance in Experiment 2 was as follows:

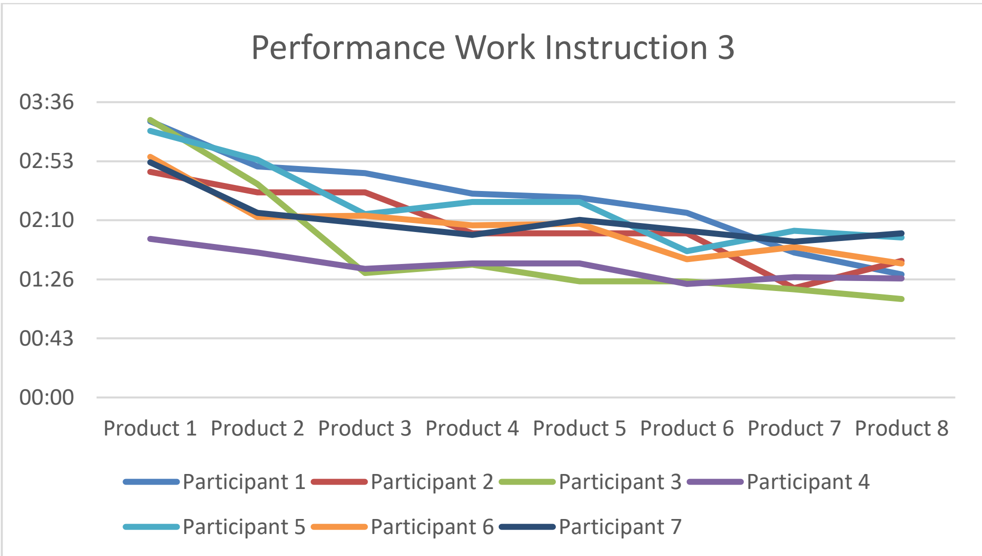

Figure 7, Performance following WI 3

The commonality that can be seen is that most participants still take longer to produce the first two products than the subsequent ones. This can be attributed to the fact that participants need certain operations to adapt to the work instructions they are exposed to for the first time. And when they become more familiar with assembly operations, they can reduce the time it takes to assemble each product.

When looking at the data for the last three products, Participants 3 (light green) and 4 (light purple) appear to be the most stable. Participant 2 (dark red) has a larger variation of about 60%. The other participants had a common variation of about 20%-30% in the production of the last three products. This shows that even the best work instruction will cause variation. If a worse work instruction is used, the variation may become higher. On the other hand, when looking at the data for the last product, the worst performer needs almost more than 50% more time to the best performer. This indicates the difference between individual workers and possible opportunities for mutual training.

The mean time and standard deviation of the participants' performance in Experiment 2 were calculated, and the variation percentage of each participant was further calculated. The formula used for calculation should be: Variation percentage=(Standard Deviation / Mean) * 100%
Where variation percentage can also be called as coefficient of variation, which shows the extent of variability in relation to the mean of the population. The results are shown in the following table:

Table 1, Variation percentage with individual mean time

Variation percentage with individual mean time			
Participant	Mean time	Standard deviation	Variation percentage
Participant 1	02:25/145(s)	33.25822	22.91695
Participant 2	02:06/126(s)	26.39099	21.00775
Participant 3	01:49/109(s)	43.20301	39.81844
Participant 4	01:36/96(s)	10.15812	10.5539
Participant 5	02:22/142(s)	27.72381	19.54101
Participant 6	02:05/125(s)	23.0431	18.37934
Participant 7	02:10/130(s)	17.09852	13.16537

It can be seen that the variation percentage of most participants is at a level of about 20%. But the data from other participants showed something very interesting. For example, mean time of participant 4 is the fastest (01:36), coupled with the lowest variation, indicating that participant 4 is both quick and consistent. Therefore, it can be suggested that other participants learn from participant 4 because of his stability. In addition, participant 3, despite having a faster mean time (01:49) than most, has the highest variation, suggesting that although he can be fast, his performance is not reliable or stable. This result may be related to the participants' personal use and preference of work instructions. When users are more familiar with the expression form and internal logic of work instructions, they may perform better.

5.2.2 Variation analysis with overall mean time

The next step is to use the overall mean time of Experiment 2 to calculate the variation percentage for each participant. According to the calculation, the mean time of work instruction 3 is 02:05. The method for calculating the variation percentage is basically the same as in 5.1, replacing each person's mean time in the formula with the overall mean time. The calculation results are as follows:

Table 2, Variation percentage with overall mean time

Variation percentage with overall mean time			
Participant	Mean time	Standard deviation	Variation percentage
Participant 1	02:05/125(s)	33.25822	26.60658
Participant 2	02:05/125(s)	26.39099	21.11279
Participant 3	02:05/125(s)	43.20301	34.56241
Participant 4	02:05/125(s)	10.15812	8.1265
Participant 5	02:05/125(s)	27.72381	22.17904
Participant 6	02:05/125(s)	23.0431	18.43448
Participant 7	02:05/125(s)	17.09852	13.67882

It can be seen that the data of each participant has changed to some extent. However, the overall situation did not change much, and most participants still maintained a variation percentage of about 20%. Individuals with larger deviations still maintain a higher variation percentage and can be considered as special cases. Therefore, it can be judged that a variation percentage of about 20% can be used as data for subsequent experimental design assumptions.

It can be said that when using the same work instruction, the inter-individual variation of participants shows the vulnerability of the work instruction. So having information about times needed by different participants over more products helps to find a direction for improvements.

5.3 Variation with different work instructions

According to the result obtained before, when using work instruction 3, participant 4 seemed to be the one who adapted best to the work instruction and performed the best. The rest of the participants can learn some skills from him. There are also possibilities that participant may have done some things when using the work instruction that were not mentioned in the work instruction, such as some personal habits. Therefore, by comparing the different performances of participant 4 when using different work instructions to make the same product, his personal variation can also be found.
According to the data obtained from the experiment, when participant 4 produced the same quantity of the same products using work instruction 2, the average time for each product was 02:23, which is much higher than 01:36. This could indicate WI 2 is either more complex, less efficient, or harder for participant 4 to follow.

To fully compare the variation between the two work instructions, the standard deviation and the variation percentage of participant 4 when using WI 2 need to be calculated:

Table 3, Variation percentage participant 4

Variation percentage participant 4			
WI	Mean time	Standard deviation	Variation percentage
WI 3	01:36/96(s)	10.15812	10.5539
WI 2	02:23/143(s)	102.9041	71.71016

Surprisingly, participant 4 performed very differently when using work instruction 2. In terms of standard deviation, the performance of participant 4 became more inconsistent, and the distribution of production time around the mean became more dispersed. The sharp increase in variation percentage indicates that participant 4 had more difficulty with consistency when using work instruction2. The process stability was greatly reduced, and the time to produce each product fluctuated greatly. Judging from the performance of participant 4, the difference in work instructions has a great impact on his personal variation when making the same product.

In order to more rigorously study the effect of work instructions on users, the data of the participant who achieved the best performance using work instructions in Experiment 2 will be extracted and compared with his/her data when using other work instructions. The participants who are chosen in the study are participant 5 and participant 6.

Table 4, Variation percentage participant 5

Variation percentage participant 5			
WI	Mean time	Standard deviation	Variation percentage
WI 3	02:22/142(s)	27.72381	19.54101
WI 2	02:23/143(s)	24.11658	23.21692

Table 5, Variation percentage participant 6

Variation percentage participant 6			
WI	Mean time	Standard deviation	Variation percentage
WI 3	02:05/125(s)	23.0431	18.37934
WI 1	01:23/82(s)	16.8949	20.29417

The two selected participants performed best among all participants when using not work instructions 3. Participant 6 performed significantly faster using work instruction 1 than work instruction 3, while participant 5's performance were very similar between the two instructions, showing little impact on efficiency. From the perspective of consistency, in both cases, the participants showed more variability (higher variation percentage) when not using work instruction 3(participant 5 with work instruction 2 and participant 6 with work instruction 1). This suggests that while some work instructions might improve speed, they tend to introduce more inconsistency in production times.

Based on the study of the data of three experimental participants, it can be concluded that different work instructions not only affect the efficiency of users, but also significantly affect their consistency and stability (personal variation).

5.4 Conclusion

After the experimental study, it can be concluded that even when users use the better work instruction at the moment, there will still be variation. This variation is about 20% in the experimental study. This output shows the relationship between time variation and work instruction in the production process and can be used as a reliable input in subsequent simulation experiments.

Another key finding of the experimental study is to conclude that measuring variability reveals about the importance of improving the work instruction. In this experimental study, there are three types of variability:

(i) The variability in time that a worker needs when using the same instruction for subsequent products.
(ii) The variability in time needed by different workers using the same work instruction.
(iii) The variability in time needed in case of different work instructions for the same product.

These differences impact not only worker efficiency but also their consistency and stability. In practice, it's essential to consider whether each of these three types of variability should be measured separately. Additionally, these differences may suggest other areas for improvement, such as optimizing instruction sequence, enhancing training or peer learning, and improving instruction visibility. Further research is needed to clarify these links and guide effective improvements to work instructions.

6 SIMULATION STUDY

According to the methodology, the step following the experimental study should be the analytical study. Due to the limited scope of the analytical study and the simplification of the model, which focuses only on a single-workstation system, it has been moved to Appendix A. The results from this study offer preliminary insights into how variation might impact system performance, serving primarily as a foundational basis for further research. In order to gain more insight into the impact of variation and improving work instructions, the simulation is required.

The simulation study aims to conduct an exploratory study to gain insight in the importance of improving work instructions to improve the output of an assembly system. This chapter will use the conceptual model mentioned in the chapter of methodology. The variation will be an intermediate impact in the model, affecting both processing time and failure rate. The direct effect of variation reduction will also be considered and tested. The variable that ultimately reflects the degree of impact is the quantity of system outputs. Additionally, discussion of the arrangement of assembly tasks for the assembly system will also be included. In this chapter, the simulation will be performed using the software Plant Simulation Tecnomatix.

The simulation will be divided into several steps following a predefined plan of improvement and using the same model. The model involved in the simulation is based on data from a real company production system. The simulation will be performed on the entire system.

6.1 Introduction of the system

The model involved in the simulation experiment is the HDS (High Dynamic Storage) Assembly System comes from Walraven. This system in developed by students of the HAN but is currently not used in practice because of a lack of production orders. It is valuable to investigate how data can be used to improve the system when it is running constantly. This study will explore this issue.

The HDS Assembly Line consists of the following stations:
Station 1: 6 ways valve.
Station 2: Bracket platform.
Station 3: Insulation of the pipes linked with the station of transportation.
Station 4: HDS final assembly station.
The simulation model of the production system is shown in Figure 8:

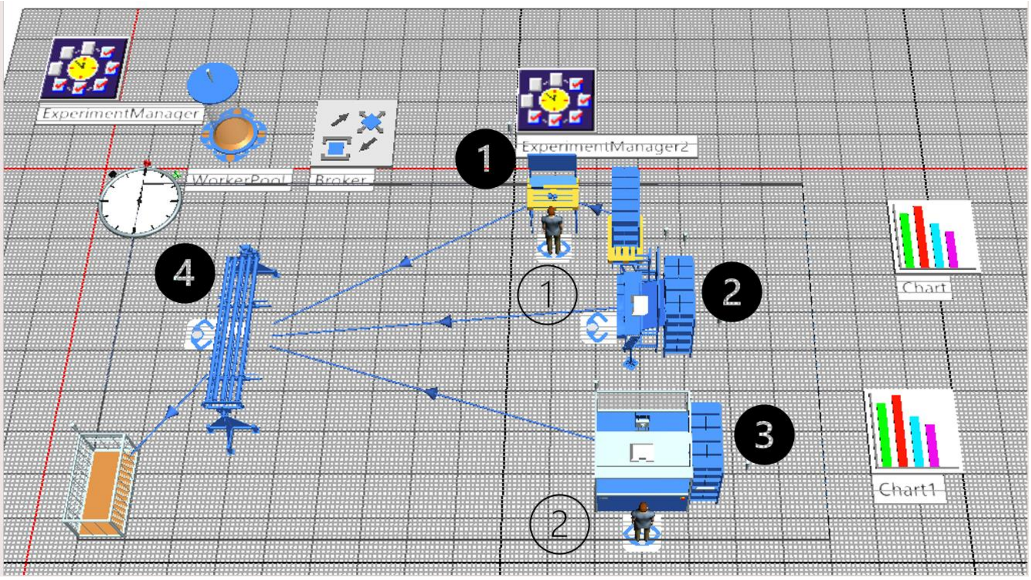

Figure 8, Simulation model of Walraven

After the products of stations 1, 2, and 3 are gathered, the station 4 will start to work for the final assembly. On average, the time it takes for each workstation to complete a product assembly task is:

Table 6, System data without variation and failure rate

Initial data of the system without variation and failure rate				
Station	6 ways valve	Bracket platform	Insulation	Final assembly
Time	2:48	3:30	11:00	8:16

Suppose there are two operators in the system who are involved in the assembly work. The two operators are assigned work based on the working time of the workstations in the system. The best balance is gained when operation 1 works on station 1, 2 and 5, and operator 2 always works on station 3. Although operator 2 always works on the same station, he will not be continuously busy.
As a result, work distribution between the two operators in the system is:
Operator 1: Works on station 1, 2 and 5.
Operator 2: Always works on station 3.

Before starting the simulation experiment, there is a very important point that needs to be mentioned. As mentioned in the analytical study, in practice there is often a buffer of components in front of an assembly system. This is the case in the simulation experiments in this chapter. As shown in the simulation model, there is a stock of materials next to each workstation to ensure that the workstation always has materials for assembly and processing. The inter-arrival time of the inputs will not be taken into account in the simulation experiments.

Each round of simulation will record the output quantity of the system for 8 hours of operation. In order to simulate the typical state of normal operating conditions in the system, a 2-hour start-up period will be added to the system, that is, the system will be run for 2 hours first, and then 8 hours of operation data will be collected. The simulation will be performed 100 times in each state to eliminate extreme random situations.

In this simulation, all variations of processing time will be represented by Erlang distribution in the software. An introduction to Erlang distribution and the comparison with other distributions are shown in Appendix B.

6.2 Plan of improvement

In this chapter, the PDCA (Plan-Do-Check-Act) method will be used repeatedly. A step-by-step improvement plan will be developed first, followed by executing it, analyzing the results, and improving the plan. Then a new round of PDCA can be proposed. The objective at the end of the chapter is to learn from it and to come up with a better plan. The performance of the system will be mainly reflected in the quantity of system output.

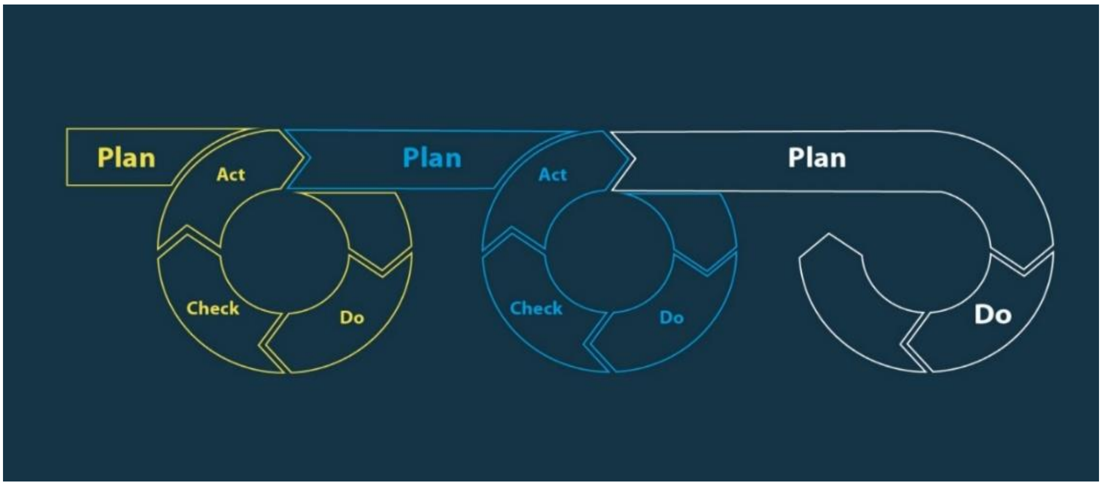

Figure 9, PDCA Cycle

In this section, a plan of improvement will be designed based on the system's status. As the initial state of the system, a 20% variation and a 5% failure rate will be added to the system, which was obtained by the previous chapters. The purpose of designing a plan of improvement is to improve the performance of the system. The specific contents can be divided into:

1. Less failure
2. Less variation
3. Faster
4. More balanced

Based on these objectives, the following improvements to the production system will be considered:

1. Implement more control (quality check) during the process of working to reduce the failure rate.
2. Implement a better work instruction to reduce the variation of the operators.
3. Provide professional training for operators centrally to reduce processing time.
4. Balance the load of the production system and eliminate bottlenecks as much as possible.

In the first round of PDCA, interaction effects (e.g., better work instructions may also lead to less failures) will not be studied. These effects can be discussed and studied in the subsequent PDCA round. Also, some of the simulation results can be obtained only through analysis. But simulation helps to visualize the results and make them closer to reality.

6.3 Quality control

Quality control will be reflected in adding more quality checks during the work process to ensure that each workstation has fewer failures during operation. Since more quality checks will take more time, the processing time of each workstation will be increased accordingly. According to 20% of variation and 5% of failure rate, the initial state of the simulation experiment is:

Table 7, Initial state of the system

Initial state of the system								
Station	6 ways valve		Bracket platform		Insulation		Final assembly	
Time/Variation	2:48	0:34	3:30	0:42	11:00	2:12	8:16	1:39

Use the above data to first simulate the system. The output quantity of the system is 30.125 products. The simulation of quality control will be carried out in steps. The main variables are the processing time and failure rate of the workstation. Since more control checks lead to higher processing time, the simulation plan is to increase the processing time of the workstation from 0% to 20% and simulate the quantity of system output when the failure rate decreases from 5% to 2.5% and 0%. Each step will increase the processing time of the workstation by 5%. The purpose of the simulation experiment is to find out under what circumstances the trade-off between processing time and failure rate can make the system perform better than the initial state.

Table 8, Output quantity Failure rate vs. Increase of processing time

Output quantity Failure rate vs. Increase of processing time					
	0%	5%	10%	15%	20%
5%	30.125	28.75	27.515	26.15	25.12
2.5%	31.425	29.975	28.6	27.32	26.25
0%	32.82	31.29	29.89	28.525	27.315

What can be seen from the table is that as the processing time of a workstation increases, the system output may decrease in the same amount of time, even if the failure rate of the workstation has been reduced or eliminated. Using line charts to visualize data can provide a more intuitive representation of the system.

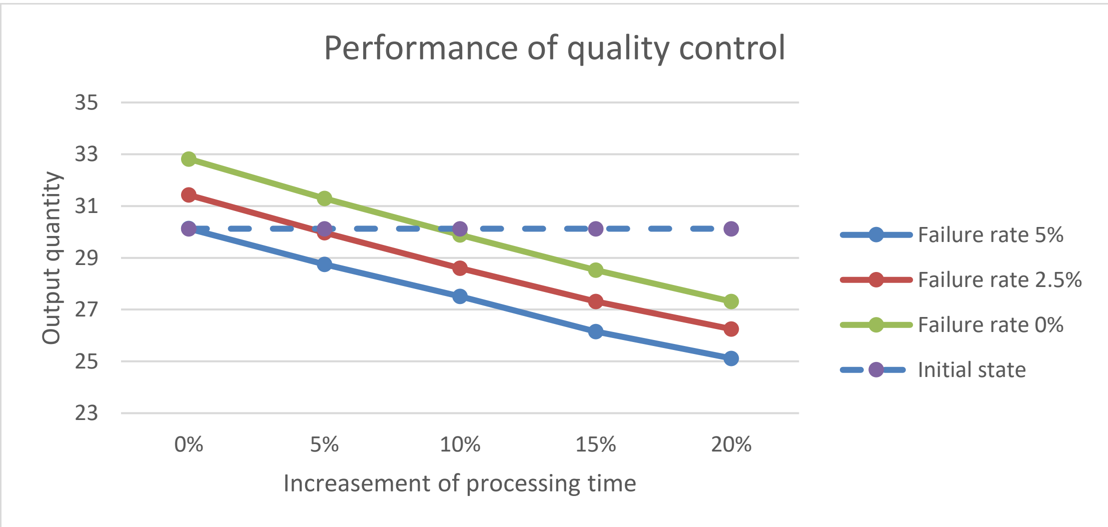

Figure 10, Performance of quality control

The chart illustrates that as processing time increases, the overall system output tends to decline, even when the failure rate is reduced or eliminated. The initial state (represented by the dashed line) serves as a baseline for comparison. In the simulation, it's observed that only when processing time increases by a minimal amount (5%) and the failure rate is completely reduced to 0%, does the system's output exceed the initial state. This combination of a slight processing time increase with a 0% failure rate proves effective because the output remains higher than in all other scenarios, demonstrating a balance between quality improvement (eliminating failures) and efficiency (minimizing processing time increase). This makes the 5% increase with a 0% failure rate an optimal approach for quality control.

This result shows that the company can consider reducing the failure rate through the method of quality control to increase the output quantity of the system. What needs to be tested and compared is the trade-off between the increase in processing time and the failure rate caused by the increase in quality control. At the same time, the result of 5% increase in processing time and 0% failure rate can be a new starting point of the follow-up simulation.

6.4 Improvement of work instruction

From the results of observational study and literature survey, improvements in work instructions may have impact on variation. The simulation in this step will continue the system output from the previous step. In this section, simulation experiments are performed to find out whether the size of this effect is worthwhile. In the previous step, due to the introduction of more quality checks, the failure rate of the system was reduced to 0%. Therefore, in this step the influence of failure rate will be excluded, and the simulation will focus on the influence of different variations on the output quantity of the system under the premise of the same processing time.

Table 9, Simulation data with improvement of work instruction on variation reduction

Simulation data with improvement of work instruction on variation reduction								
	6 ways valve		Bracket platform		Insulation		Final assembly	
Variation 20%	2:56	0:34	3:40	0:44	11:33	2:18	8:40	1:44
Variation 10%	2:56	0:17	3:40	0:22	11:33	1:09	8:40	0:52
Variation 5%	2:56	0:08	3:40	0:11	11:33	0:34	8:40	0:26
Variation 2%	2:56	0:03	3:40	0:04	11:33	0:13	8:40	0:10

The data of the workstations involved in the simulation are shown in the table above. Starting from 20% variation, the variation is reduced to 10%, 5% and 2% respectively while keeping the same processing time. Use a line chart to visualize the output quantity of the system, and the result is shown in the following figure:

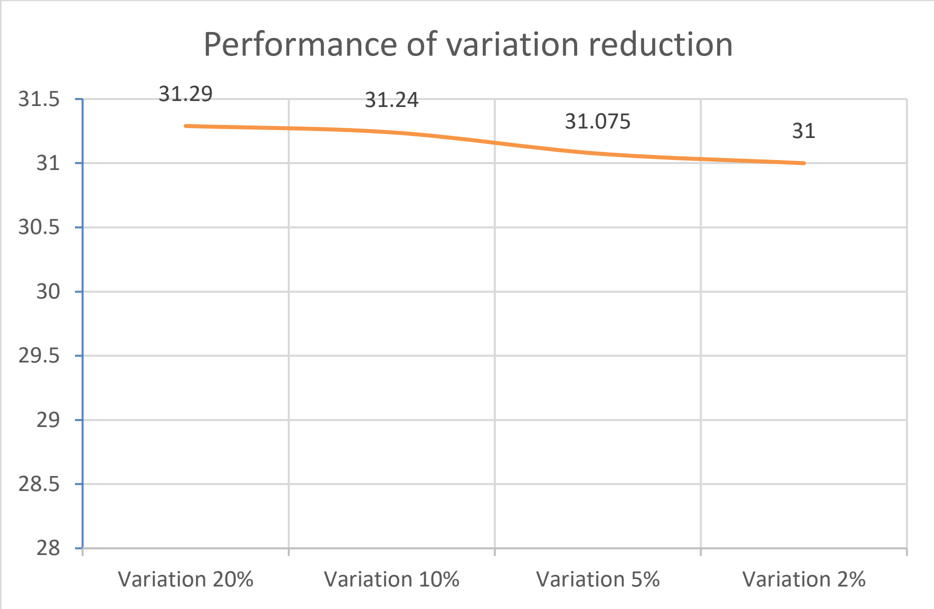

Figure 11, Performance of variation reduction

The result of simulation here is not significant. Generally speaking, with the same processing time, fewer variations will lead to a higher number of outputs. However, the data of simulation shows that under the current state, fewer variations may even lead to a lower number of outputs. It would be difficult to explain it. But it can be said that the differences are very small and not relevant. It is also logical that the differences are minimal, because the average time that operator 1 needs remain equal in all situations studied in this step. It is still possible to draw conclusions, if reduction of the variation is the only reason to improve the work instruction, then it's not so worthwhile. And relatively speaking, the average processing time has a greater impact.

6.5 Professional training for operators

Professional training is widely recognized as a key strategy for enhancing operator performance. According to research, good professional training has an effective impact on improving the level of operating elements and improving work efficiency in at least 80% of cases (Edwards, Cabahug, & Nicholas, 2003). Another finding suggests that specialized training can address significant training needs and help reduce inconsistencies (Midden, 2024).

The results in the previous step show that reducing variation to very low levels do not significantly improve output. Therefore, in this step, the simulation will still start from the results obtained from quality control. Therefore, in this step, the simulation will still start from the results obtained from quality control, that is, a 5% processing time increase and a 0% failure rate. The aim is to examine whether the efficiency gains from professional training alone are sufficient to increase production

In this step, the effects of professional training on processing time reduction of 5%, 10% and 15% will be simulated. These reductions represent the potential benefits of training aimed at improving operator speed and efficiency. The system data involved in the simulation experiment are shown in the following table:

Table 10, Simulation data with professional training

Simulation data with professional training								
	6 ways valve		Bracket platform		Insulation		Final assembly	
Before training	2:56	0:34	3:40	0:44	11:33	2:18	8:40	1:44
Training 5%	2:47	0:33	3:29	0:41	10:58	2:11	8:14	1:38
Training 10%	2:38	0:31	3:18	0:39	10:23	2:04	7:48	1:33
Training 15%	2:29	0:29	3:07	0:37	9:49	1:57	7:22	1:28

The simulation results are still expressed using the quantity of system output. Use a line chart to visualize the output data, as shown below:

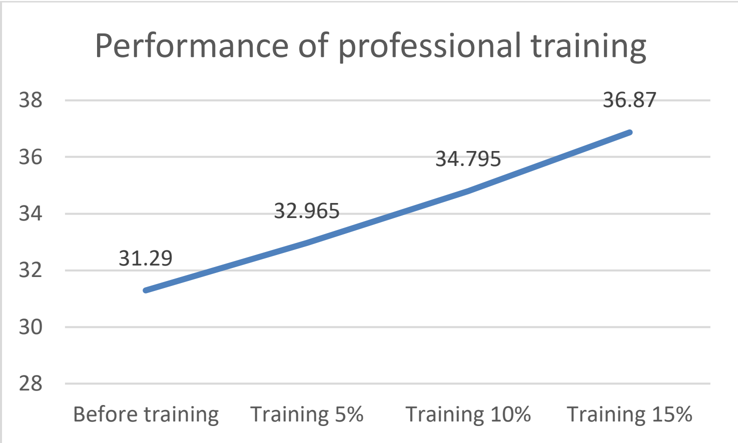

Figure 12, Performance of professional training

From the results, it can be seen that every reduction in processing time has a positive impact on the output of the system, indicating that there is a direct correlation between improved processing efficiency and increased throughput. This result demonstrates the effectiveness of professional training in improving productivity. But in fact, this result can be obtained analytically, as mentioned in the plan of improvement. The simulation is useful to visualize and animate results and in case mixed scenarios (e.g. measures on each station is different) are made.

Compared with improving work instructions to achieve variation control, the reduction in processing time caused by training provides a better and continuous improvement. This supports the view that professional training can produce substantial, measurable benefits.

6.6 Workload balancing

In the literature review, it was mentioned that if one phase of the assembly process consistently takes longer than the others, then tasks can be reallocated or more resources can be allocated to that phase. The conclusion of the improvement of work instruction also mentions that balancing adjustments to workstations that are close to or have become bottlenecks in the system may produce impactful improvements.

In the system model used in this simulation experiment, station 3 (insulation) takes the longest time and is always worked by one operator (operator 2). The other operator (operator 1) needs to complete the work of station 1 and station 2 first, and then wait for station 3 to complete its assembly work before starting to work at station 4 (HDS final assembly). According to the time data of the initial state of the system, operator 1 will spend more time than operator 2 in a complete product assembly process. Therefore, it can be judged that the bottleneck of the system is the operator 1. Balancing the working time between the two operators may be a solution to improve the system's performance.

In this section, the total working time of the two operators will be averaged, which is specifically represented by moving part of the processing time of station 4 to station 3. The data involved in the simulation will use the system performance after the best professional training in the previous section, which is 15% processing time reduction, 0% failure rate and 20% variation. The results of the simulation are shown in the following table:

Table 11, Simulation data with workload balancing

Simulation data with workload balancing									
Time/ Variation	6 ways valve		Bracket platform		Insulation		Final assembly		Output quantity
Initial	2:29	0:29	3:07	0:37	9:49	1:57	7:22	1:28	36.87
Balanced	2:29	0:29	3:07	0:37	11:23	2:16	5:47	1:09	40.66
Variation 0%	2:29	0	3:07	0	11:23	0	5:57	0	42

The total processing time of the system is: $2{:}29 + 3{:}07 + 9{:}49 + 7{:}22 = 23{:}47$. When the working time of two operators is divided equally, each operator needs to perform $\frac{23:47}{2} = 11{:}23$ of work. Therefore, the processing time of station 3 insulation was adjusted to 11:23, and the time of station 4 final assembly was reduced accordingly to obtain the above simulation data.

From the results, balancing the workload achieves higher system output, which means that the system's workflow may become smoother. The improvement is significant, so it can be said that balancing stations 3 and 4 helped shift the bottleneck and reduce delays in the final assembly process. Further simulations were performed to reduce the system's variation to 0%. The system's output quantity was further improved. This means that reducing variation after balancing the system's workload can have a positive impact on the system. It can be said that the method of improving the work instruction to reduce variation in section 7.4 may have a greater positive impact on the system if it is used after the system workload is balanced. The reason may be that if the variation is large, it will shift the bottleneck.

6.7 Discussion

Through the results of the simulation experiment, the plan of improvement proposed in section 7.2 can be summarized. Among them, first, the trade-off of increasing processing time and reducing failure rate during quality control can improve system performance, but the improvement is not particularly large. Subsequently, improvements to the work instruction aimed at reducing variation were also not particularly ideal. As additional steps, professional training and workload balancing can have a significant positive impact on the simulation system. But this doesn't mean that the steps in the first two improvement plans are completely meaningless. Some discussion can be had on the purpose and methods of system improvement, because there are actually some connections between each step in the plan of improvement. A relationship matrix can be used to show the connections between them:

Table 12, Relationship matrix of improvement methods

Relationship matrix of improvement methods				
	1	2	3	4
1. Quality Control		O	O	O
2. Variation Reduction (better WI)	+		+	O
3. Professional Training	+	+		O
4. Balancing	O	O	O	

- **"O"** indicates no relationship between the methods.
- **"+"** indicates that one improvement method can positively support or include another.

From this relationship matrix, there are many correlations between implementing a better WI and other methods. For example, a better WI may improve the quality (less failures), so it reduces the need to have some quality controls. At the same time, the reason for professional training may also be that the company wanted less variation, and the effect of training may also be related to it. In terms of balancing, adjusting workloads between stations may require updating the work instruction to provide operators with precise, newer guidance suited to new workload levels.

This interdependence suggests the idea that better work instruction leads to less variability and may also lead to better quality and shorter (or other) processing time. In other words, better WI strengthens the foundations on which quality control, training, and balance are built. These relationships can be explored more explicitly by proposing a relationship matrix of the links between each improvement method and the key objectives of the improvement plan.

Table 13, Relationship matrix of improvement methods and objectives

Relationship matrix of improvement methods and objectives				
	Better WI	Quality control	Training	Balancing
Fewer failure	+	+	+	-
Less variation	+	-	+	-
Faster	+	-	+	+
More balanced	-	-	-	+

- **“+”** means the improvement plan helps achieve the specific purpose.
- **“-“** means the improvement plan does not significantly contribute to or might even hinder that purpose.

From this matrix, it can still be found that better work instruction can actually serve as the basis for an improvement plan because it can have a positive impact on multiple improvement objectives. Balancing is a special case. It can be said that other improvement plans are aimed at optimizing the performance of operators, while balancing is to redesign the entire system.

6.8 New plan of improvement

Based on the simulation results and the discussion in the previous section, a new plan of improvement can be redesigned for the current system. The order of facts for this improvement plan is:

1. Workload balancing
2. Improvement of work instruction

3. Professional training
4. Quality control

First, balancing is a background activity as a redesign of the system. In reality, a better work instruction on a station may have impact on the balance in the whole system. So, perhaps it is wise to start with balancing. After improving the system itself, focus on possible performance improvements for the operator. Improved work instruction is placed before the other two improvement methods because it is closely related to the other two methods. If the new work instruction is good enough, it may be possible to skip the training stage and include quality control tests. Of course, an improved work instruction may also require professional training for operators to facilitate their adaptation. This professional training can also be TWI (Training Within Industry), allowing better performing operators to teach each other. Finally, if the system still has a failure rate, the system will be quality controlled. This will be the last solution to ensure that the system has a good performance.

For the redesign of the improvement plan, the system can be simulated again. The data used in the simulation will be the same as the data obtained by each method in this chapter, only the order will be replaced with the new improvement plan. The system output quantity obtained at each step is used as the simulation result and visualized using a line chart. The results are shown below and compared with the improvements made in the first PDCA round:

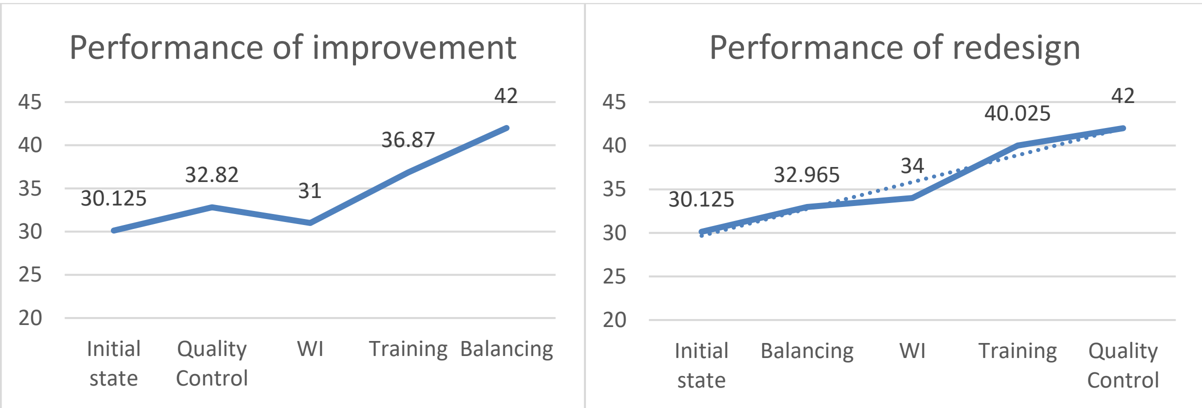

Figure 13, Comparison of improvement plan

It is evident that with each improvement step in the redesign, there is a clear positive progression in system performance, indicating that each step makes a meaningful contribution to the overall performance improvement. Therefore it is superior to the improvement plan proposed in the first round of PDCA.

In addition, from the line graph, using better work instructions to reduce variation has a positive effect under the current improvement plan, but this effect is smaller than other methods. The simulation results of this method are shown separately, as shown in the following figure:

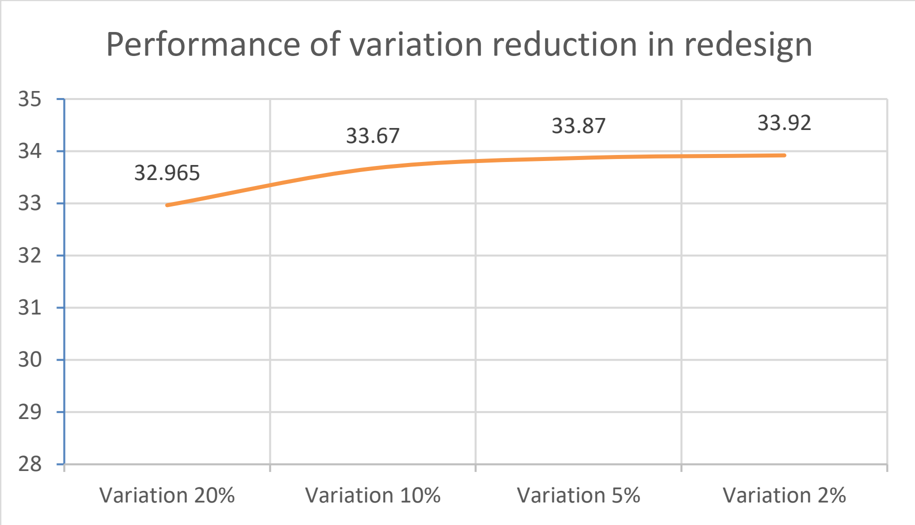

Figure 14, Performance of variation reduction in redesign

This time the simulation results are more logical, that is, lower variation leads to higher output quantity in average. However, it can be noted that this method still has limited effect on improving the quantity of product outputs. As in the previous simulation, the small improvement is due to the endless availability of material. Thus, the input buffer absorbs the changes. The result after redesign is better than the last time, so it can be concluded that the more balanced the workload of the two operators is, the greater the effect of reducing variation.

Another thing that can be seen from the redesign is that the impact of balancing the workload is huge. Although balancing, as the first step in redesign, does not seem to have the greatest impact on the quantity of system output, it has a great impact on the subsequent improvement steps, and thus will amplify the effects of subsequent improvements. Because it almost eliminates the bottleneck of the system (at this time, the variation that still exists may cause the bottleneck to still exist).The impact of improving work instruction is not directly on the output, but more indirect, because it might reduce the number of failures and might reduce the processing time needed. The companies have to estimate those effects whether or not to improve the work instructions.

Finally, the current redesign can help the system improve its performance. It can also become the input of a new round of PDCA cycle to find a better plan of improvement. For example, more interaction effects can be introduced, or different improvement methods can be considered to have different degrees of effect on different stations.

7 DISCUSSION

There are two main questions in this study, and different methodologies are used to study and answer the relevant contents of the questions. At the beginning of the study, an observational study was conducted to determine the current status and potential development of work instruction in SMEs with high variety and low volume characteristics. Through the discovery of this result, the literature review part studies the methods on how to improve work instructions. For most companies, improving work instructions can start with choosing a suitable presentation of work instruction. The presentation can be based on the operator's skills and education level and combined with other technologies, such as multimedia presentations, AR technology, or visual design based on text and pictures. The goal of these methods is to improve the entire production assembly system through better work instructions. In observational studies, it was found that many companies tried to reduce the variation in operators' work through a more adapted work instruction, but in the literature research process, it was rare to find a very strong reference to prove how much impact the work instruction can have on variation.

The purpose of the experimental study is to try to find the relationship between variation and work. In the early stage of the experiment, the variation would not be a large value, such as about 5%, but after actual analysis, it was found that even in a simple assembly work, the variation can still reach an impact of about 20%. Introducing this effect into the actual assembly production process may result in even greater changes in the results.

The analytical study nicely demonstrates how important variation is even in a simple system. Even if the actual output of the system does not change, implementing different improvements to the system can still significantly improve the system's performance. However, in most practical situations, analytical studies do not reflect reality very well, because in practice there is often a buffer of components in front of an assembly system. So, the arrival rate of products can be seen as constant. The deficiencies in this part are made up by simulation experiments.

Simulation studies demonstrate the impact of improvement methods on an actual system. The simulation results of reducing the variation are actually very interesting, because generally speaking, less variation often means better system performance, which may be related to more system output. However, the simulation results do not show this. In the first simulation of the system with reduced variation, the number of system outputs decreased slightly as the variation decreased. Of course, this is also a specific case. In the system modelled in simulation, there are two parallel operators. In reality, there is often a line of operators (serial dependencies). This might give some other results because of interactions caused by variability of processing time. In the second round of PDCA, the improvement plan was redesigned and the order of the improvement methods was adjusted. In the simulation of variation reduction this time, the results showed that smaller variation leads to higher output on average. Since the system workload balance was implemented first in the new improvement plan, this result shows that the more balanced and average the workload of the two operators, the greater the effect of variation reduction.

Higher production and better system performance are always the goals of most companies. For companies that want to improve the current production system through some improvement plans, it is very wise to collect data on variation and failure rates. Simulation can provide valuable insights into where to begin with improvements and which specific changes are most likely to have a meaningful impact, especially in the case of more complicated assembly systems, for example, systems with more serial operators. It can be seen that some companies seem to be on this path. For example, companies in observational experiments are using self-designed software to collect relevant data, while other companies have begun to consider discussing and analyzing the collected data. This is a point that is very helpful for the future development of the company.

Despite the results obtained, the experiments in this study still have limitations. For example, the simulation experiments in this project have limitations because they only consider the performance of average operators. In reality, there is no such thing as an "average person". In future experiments or simulations, it should be useful to simulate the impact of operators of different levels on the system at work, for example, simulating five groups of operators and setting their efficiency between 100% and 80%. In addition, in this project, it is simply assumed that the improvement of work instruction and training has the same effect on all stations. But in practice it can not be always like that. There might be certain station where work instruction is worse and training does not have a good effect. Therefore, future experiments can consider station correlation, that is, collect the actual effect of each improvement method on each station.

Finally, if a company attempts to improve its assembly system using the methods discussed in this project, it still needs to consider the cost and benefit issues before each step. For example, balancing the workload may require changing the stations in the system, and professional training may take some time. If the cost of an approach is not enough to obtain the corresponding benefit, it may be a wise choice for the company to consider skipping this step.

8 CONCLUSIONS

This research addresses the research questions:

- *What are the possibilities to improve the work instructions under the high variety low volume environment?*
- *How to integrate the improvement of work instructions to improve the output of the assembly systems.*

The first research question was mainly answered in the observational study and literature survey. From the perspective of presentation of work instruction, a more achievable and simpler approach is to consider clearer multimedia formats. At the same time, visual design can be added to explanatory images and text to emphasize key points and avoid failures of operators. For companies with sufficient costs, they can also consider developing work instructions using 3D animation as presentation.

The logic of sequence emphasizes that some rules can be followed when creating and improving work instructions, such as task dependencies and workflow efficiency. Paying attention to task dependencies when ordering the steps in a work instruction can help users understand the logic of the steps more easily. Workflow efficiency, on the other hand, may require the company to collect data on a work instruction that has already been put into use. Eliminating redundant steps and balancing workloads would be of great discussion value. In addition, flexibility can also be considered in terms of sequence to respond to situations that may arise during the production and assembly process.

The second research question was answered through experimental study, analytical study and simulation study. The studies gradually explored the connection between variation and work instruction, the importance of variation, and used an illustrative example from an actual company to provide companies with suggestions on how to integrate and improve work instructions. The simulation experiment went through the PDCA cycle. The final results showed that four methods can be used to improve the simulated assembly system: workload balancing, improving work instructions to reduce variation, professional training, and quality control. Depending on the impact on the system output volume, workload balancing will be arranged first. The remaining three methods may have interaction effects. The companies have to estimate those effects whether or not to improve the work instructions. At the same time, it is recommended that companies always need to consider situation dependent and evaluate the relationship between costs and benefits. Of course, the most important is, it is wise for the companies to always collect the data (failure rate, variation, output quantity…) in order to support the analysis and simulation.

For future research, it is recommended to analyze how each improvement method impacts different stations and operators. Additionally, studying more complex systems—such as those with multiple sequential operators or serial workstations—could provide further insights.

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APPENDIX A ANALYTICAL STUDY

In the experimental study, the relationship between different types of variation and work instructions was obtained by analyzing the experimental data, and 20% variation can be used as a reference for the experiment. This data will serve as a reference for variation in this chapter. In this chapter, the analytical study will further explore how important variation is. Through a simple experimental design, we will find the possible impact of variation on the system and obtain a more reliable basis through calculation.

1. Computational experiment

In this section, a computational experiment will be designed. The computational experiments will be performed based on Kingman's equation, and the results of the calculation will be discussed. First, Kingman's equation will be repeated, as:

$$W_q = \left(\frac{C_a^2 + C_e^2}{2}\right)\left(\frac{u^{\sqrt{2(m+1)}-1}}{m(1-u)}\right) t_e$$

Where:

$ta = average\ arrival\ time$

$te = mean\ processing\ time$

$c_a = coefficient\ of\ variation\ of\ arrival\ times = \frac{\sigma_a}{t_a}$

$c_e = coefficient\ of\ variation\ of\ process\ times = \frac{\sigma_e}{t_e}$

$m = number\ of\ parallel\ servers\ at\ a\ station$

$Ra = arrival\ rate$

$Re = processing\ rate$

$u = utilization\ of\ station$

$Wq = expected\ waiting\ time\ in\ the\ queue$

Assume that a simple system only have one workstation, so in this experiment, $m = 1$ is selected. The equation will transform into:

$$W_q = \left(\frac{C_a^2 + C_e^2}{2}\right)\left(\frac{u}{1-u}\right) t_e$$

First, design the initial conditions for the system:

$c_a = 1$, which means a negative exponential arrival rate, which is quite high and means that arrivals are independent from each other.

$c_e = 0$, which means currently no variation caused by the operators in processing time.

$u = 90\%$, which means that the system is busy during 90% of the time.

$te = 10{:}00$. The mean processing time will be changed by implementing a new/better work instruction.

This chapter only studies a one station assembly situation where the average arrival rate is fixed with a negative exponential distribution. Average throughput time is here the performance measure (dependent variable). This situation is important in situations of independent customers, for example, a shoe repair shop, an ice selling shop, or an employee who has to do the order picking in a warehouse in order to provide different assembly workers who ask for components.

Based on the data above, the expected waiting time in the queue Wq can be calculated. These data show that the system works perfectly (no failure rate, no variation).

An important setting is the potential failure rate of the system. In the initial state, the failure rate is set to 0%. After that, the system will be given a failure rate of 5%. In this study, failures will be seen at the end of the assembly. After found a failure, the station needs to assemble an extra product . Therefore, when the system includes the failure rate, the actual average number of completed products will be greater than the initial state, but the actual output of the system will not change. This is slightly different from the conceptual model, so in the analytical study, $W_q = expected\ waiting\ time\ in\ the\ queue$ will be used as the criterion for judging the system's performance.

Another thing to note is that analytical study is a poor representation of the reality in most practical cases. The model relies on simplifying assumptions—like steady-state conditions and isolated workstations—that ignore the dynamic and interconnected nature of actual production lines, leading to a model that lacks practical realism. While useful for theoretical insights, analytical studies provide only a partial view and should be supplemented by empirical data or simulations to capture the complexities of real-world systems effectively.

Calculations will be done primarily through Excel. And part of the calculation process will be omitted and will be shown in the appendix. It is divided into several steps.

Table 14, Calculations with Kingman's equation

Calculations with Kingman's Equation						
Step	Ca	Ce	u	te	Wq	
1	1	0	90%	0:10:00	0:45:00	Initial state
2	1	0.2	94.5%	0:10:00	1:29:21	Suppose variation + failure rate
3	1	0.1	99.2%	0:10:30	10:57:31	Only change the variation with higher processing time
3	1	0.2	94.5%	0:10:30	1:33:49	Only change the failure rate
3	1	0.1	89.8%	0:09:30	0:42:14	Only change the variation with lower processing time
4	1	0.1	94.5%	0:10:30	1:31:06	Suppose more control (changing the WI) and with 0 failure rate
4	1	0.1	93.78%	0:10:25	1:19:19	Suppose a new data of processing time to observe the impact
4	1	0.1	85.5%	0:09:30	0:28:17	Best situation (less failure, less variation and less processing time)

- Step 1. Initial state (base step)

According to Kingman's equation, calculate the value of the expected waiting time in the queue when the system working without variation and failure rate. This value is difficult to achieve in actual production process.

- Step 2. Suppose variation + failure rate

Assume that there is variation in the system because of bad work instructions or a lack of standard skills which require training. This variation may also lead to failure rate of the system. Using the conclusions from the experimental study, the size of the variation will be 20%, that is, c_e will be adjusted to 0.2. The failure rate of the system will also be considered. When a 5% failure rate is added to the system, the actual utilization of the system will change according to the definition of failure in the system.

The calculation is as follows:

Products produced with 90% utilization per hour: $\frac{60}{10} \times 90\% = 5.4$ products.

Expected number of reworked products with 5% failure rate: $5.4 \times 5\% = 0.27$ products.

The actual total number of products: $5.4 + 0.27 = 5.67$ products. It should be noted that the average hourly output of the system is still 5.4 products/hour.

The new utilization: $\frac{5.67}{6} \times 100\% = 94.5\%$.

Using this utilization, the performance of the system when it is affected by both variation and failure rate can be calculated. This data is closer to the actual situation. It is obvious that the expected waiting time in the queue has almost doubled compared to the initial state. This shows that even if the actual output of the system does not change much, the variation and failure rate still have a great impact on the performance of the system.

- Step 3. Suppose control method only on variation and only on failure rate

In this step, it is assumed that control steps are added to the work instructions , which will change the processing time to a certain extent, but relatively speaking, reduce the variation or failure rate alone as a trade-off.

First consider the case where processing time increases. Keeping the production volume unchanged, increase the processing time to 10:30 and reduce the variation to 10%. This change will also affect the utilization of the system.

The calculation is as follows:

Products produced with 90% utilization per hour: $\frac{60}{10} \times 90\% = 5.4$ products.

Utilization without failure rate: $\frac{5.4}{\frac{60}{10.5}} \times 100\% \approx 94.5\%$

Effective production time: $60 \times 94.5\% = 56.7$ minutes.

Expected number of reworked products with 5% failure rate: $5.4 \times 5\% = 0.27$ products.

Additional time for rework: $0.27 \times 10.5 = 2.835$ minutes.

The total active time: $56.7 + 2.835 = 59.535$ minutes.

The new utilization: $\frac{59.535}{60} \times 100\% \approx 99.2\%$.

From the definition of utilization, 99.2% is a high value, which will lead to lack of flexibility and higher risk of bottleneck in the system. The expected waiting time in the queue calculated accordingly is also very high.

Assuming that this control measure increases processing time and only affects the failure rate, the variation can be changed back to 20% and use the calculated utilization of 94.5%. As a result, the expected waiting time in the queue is still higher than when no control measures are used. But the gap is not very large. Adjusting the increase in processing time and the decrease in failure rate may yield valid data.

Therefore, in the current system, the control method of only improving variation is not particularly applicable. Because in this case, the utilization of the system has reached a very high level, and the expected waiting time in the queue has also increased significantly. On the other hand, the control measures implemented on the failure rate may serve as an effective reference.

In fact, there is a possibility for the variation control method to reduce the variation while reducing the processing time. Assume that in this case, the processing time of the system is reduced to 9:30. As the processing time decreases, a new utilization is needed to be calculated.

The calculation is:
Products produced with 90% utilization per hour: $\frac{60}{10} \times 90\% = 5.4$ products.
Utilization without failure rate: $\frac{5.4}{\frac{60}{9.5}} \times 100\% \approx 85.5\%$
Effective production time: $60 \times 85.5\% = 51.3$ minutes.
Expected number of reworked products with 5% failure rate: $5.4 \times 5\% = 0.27$ products.
Additional time for rework: $0.27 \times 9.5 = 2.565$ minutes.
The total active time: $51.3 + 2.565 = 53.865$ minutes.
The new utilization: $\frac{53.865}{60} \times 100\% \approx 89.8\%$.

From the calculation results, the expected waiting time in the queue has been greatly reduced. In most cases, it is difficult to simultaneously reduce variation and reduce processing time. Such improvements may occur in specific circumstances, for example, if professional training is included in the control method or if the system equipment is optimized to reduce processing time.

- Step 4. Suppose more control (changing the WI) and with 0 failure rate

The last step is consistent with what was mentioned in the conceptual model, which is to introduce a new/better work instruction, which affects both processing time and failure rate due to the change in variation. Intuitively, it reduces the variation to 10%, increases the processing time to 10:30 or reduce the processing time to 9:30, and eliminates the failure rate of the system (under ideal conditions).
According to the calculation results in the previous step, utilization should be defined as 94.5%. The utilization value is somewhat coincidental because it is the same as the system's original value with variation and failure rate. The Wq calculated from this set of data has some positive changes compared to the data in step 4. But what is interesting is that compared to the data assumed in step 3 for failure rate and variation, Wq has increased somewhat, although these increases are not very large. This may be due to the same utilization. In order to draw a clearer conclusion, we can make a

small change to the data involved in the calculation. The other calculation data remain unchanged, and the mean processing time is changed to 10:25, which is 10.42 minutes.

Based on this processing time, the utilization is recalculated:
Products produced with 90% utilization per hour: $\frac{60}{10} \times 90\% = 5.4$ products.
New utilization without failure rate: $\frac{5.4}{\frac{60}{10.42}} \times 100\% \approx 93.78\%$

Using the new utilization to participate in the calculation, the result of Wq obtained is significantly different from that in step 3. After implementing more controls, the system performance had a positive impact of more than 10% on the expected waiting time in the queue.

Finally, the best case scenario with less failure rate, less variation, and less processing time is calculated. According to the calculation results in the previous step, utilization of this situation should be calculated as 85.5%. The calculation results of expected waiting time show that this is indeed the best state that the system can achieve after improvement.

2. Conclusion

After the analytical study, it can be concluded that a good control method or an improvement on work instruction will have impact on the system. Although the system output quantity has not changed, the performance of the system was still improved, as reflected in the improvement of utilization. But from this result, it seems that impact on utilization is the most important factor.

The shortcoming of the study is that this study only considers a simple production system consisting of one workstation, so the impact of the factors on the system may be limited. If simulation experiments or calculations are considered in a more complex system, a more intuitive and reliable result will be obtained to support the current conclusion, because the results are closer to reality.

Furthermore, in practice there is often a buffer of components in front of an assembly system. In case of an assembly system where components are always available, the output of the system is probably the most important performance indicator.

APPENDIX B ERLANG DISTRIBUTION

In simulation study, in order to set up variations for the simulation system in software, it is needed to choose a distribution type for the stations. This chapter discusses the Erlang distribution and the reasons for choosing the Erlang distribution as the simulation model setting.

1. Introduction of Erlang distribution

The Erlang distribution is a generalization of the exponential distribution. While the exponential random variable describes the time between adjacent events, the Erlang random variable describes the time interval between any event and the kth following event. A random variable x_k is referred to as a kth-order Erlang (or Erlang-k) random variable with parameter λ if its Probability Density Function is given by:

$$f_{x_k}(x) = \frac{\lambda^k x^{k-1} e^{-\lambda x}}{(k-1)!} \quad for\ x, \lambda \geq 0$$

(Ibe, 2013)

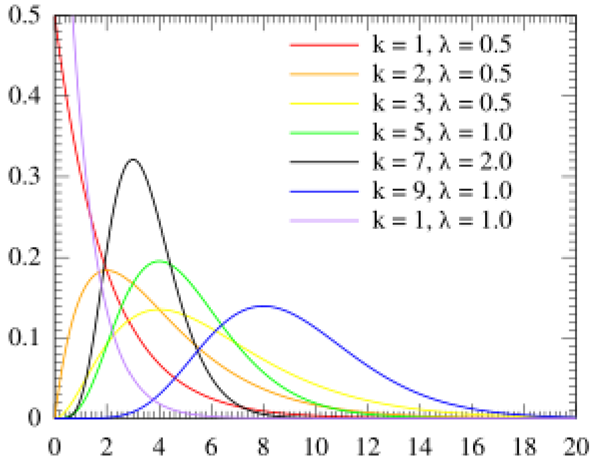

Figure 15, Probability density function of erlang distribution

The Erlang distribution was developed by A. K. Erlang to examine the number of calls that a switching station operator might make simultaneously (Rodríguez-Dagnino & Hideaki, 2010). In manufacturing, the Erlang distribution is sometimes used to model production systems. Here are the reasons:

- Realistic processing time modeling: The processing time in a real-life system often doesn't follow a strict normal or expnential distribution. They might have a skewed distribution with a peak around the average processing time and a right tail for longer processing time.
- Suitable for queueing theory: In queueing theory, the Erlang distribution is widely used to model service times in system. In the model of manufacturing systems, the tasks are often break down into several sub-steps. So the Erlang distribution can capture this type of variability easily.

In addition, a simple comparison can be made between the Erlang distribution and other distributions.

2. Comparison with other distributions

The previous section described why the Erlang distribution is suitable for simulating the system variation in this master project. This section will make some simple comparisons between the Erlang distribution and other distributions to further prove that the Erlang distribution is suitable for this simulation experiment.

- Normal distribution: The normal distribution is symmetric around the mean, which is not possible in practice. Processing times in manufacturing are often skewed to the right (longer times are less likely, but possible). So the normal distribution cannot be used here.
- Exponential distribution: The exponential distribution is heavily skewed to the right, meaning there's a high probability of very short times and a long tail of much longer times. This tends to be less likely to occur in manufacturing and therefore is not applicable.
- Log-normal distribution: The lognormal distribution is right-skewed, but it will generally produce tails that are heavier than typical processing times, which are less likely to have extremely high times. This can lead to an overemphasis on longer durations, making them impractical for most manufacturing steps.

In summary, the Erlang distribution is a good choice for simulating processing time in this master project.