Methodically improving assembly lines

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24 July 2020
IPD

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This report proposes a sequence of methods for improving assembly lines on the following five aspects:

- Assembly time
- Product quality
- Assembly costs
- Assembler workload
- Faulty bicycles amount

This method is depicted in figure 1. The influence of the application of this method sequence on an assembly line is tested and measured.

To test the methods, the assembly line of Accell's most produced bicycle is used as a case study.

The company Accell designs and assembles regular bicycles and electronic bicycles. In Heerenveen, an assembly plant assembles 250 different bicycle models. The assembly of these bicycle models is done on 7 assembly lines. At these assembly lines, workers fasten parts to bicycle frames. Assembling electronic bicycles is a costly, time-consuming and labour-intensive process, which requires 16 assemblers XXX minutes to perform per bicycle.

The influence of the applied methods on the assembly line is done in two ways. First by comparing the assembly times of the assembly line situation to the situations in which improvements based on the applied method are implemented.
Second, measuring the influence of the applied methods on the five aspects. This is done by quantifying the aspects into a list of requirements to which an ideal assembly operation adheres. The assembly line situation and proposed assembly situation are compared to the list of requirements to determine if the application of the method has improved the assembly line on the five aspects. To verify if the sequence of methods can be used to structurally improve assembly lines, the following hypotheses are tested:

Null hypothesis aH0: The application of the proposed methods does not affect assembly time.

Research hypothesis aH1: The application of the proposed methods reduces assembly time.

Null hypothesis bH0: The application of the proposed methods does not reduce the amount of list of requirement violations.

Research hypothesis bH1: The application of the proposed methods reduces the amount of list of requirement violations.

The hypotheses were tested for three assembly operations. The outcomes of the three tests were 13.3, 3.8 and 1.1 seconds of assembly time reduction and 22, 7 and 2 reductions of list of requirement violations.

The deliverables for this project are:
1. A method for determining the largest assembly time reduction opportunities and structurally generating improvements.
2. An overview of the ABC Model assembly line detailing the largest improvement opportunities.
3. A multitude of ideated and tested improvements for the largest time reduction opportunities.

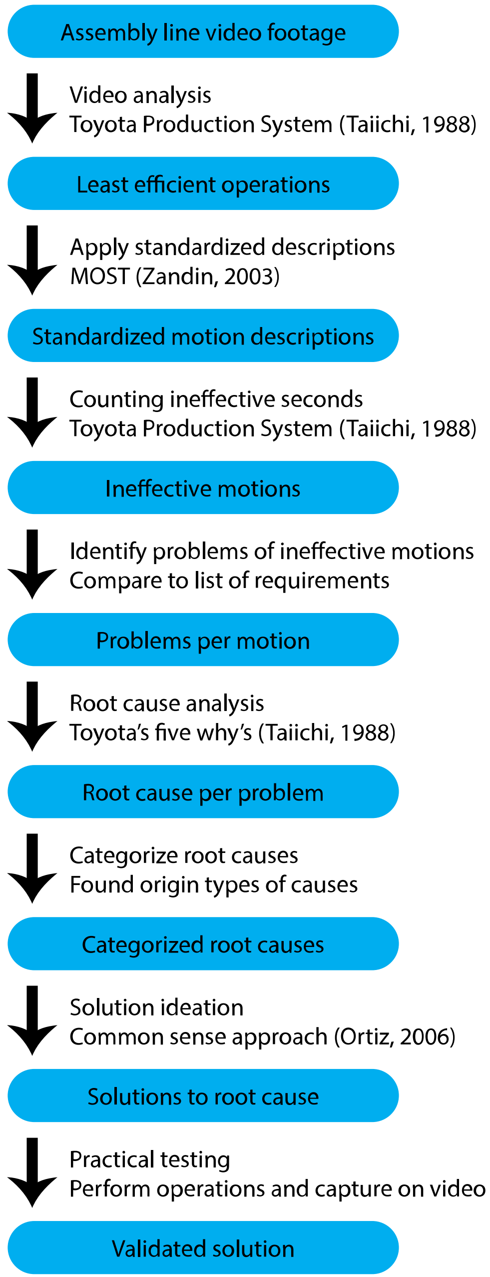

Fig. 1 Overview of method sequence.

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1. Introduction

Introduction · Situation · Theory · Ideation · Concept · Testing · Results · Conclusion · Discussion

1 — 2 — 3 — 4 — 5 — 6 — 7 — 8 — 9

The introduction chapter aims to make the reader familiar with the project. First, to understand the current situation and the goals of the client company, Accell's background is detailed in chapter 1.1. Next, to explain why the most produced bicycle was chosen as case study,. This bicycle is detailed in chapter 1.2. Then, to clarify the setup of the project, the research plan is described in chapter 1.3. After that, to illustrate the origins of Accell's goals, the sub-questions which investigate the goals are described in chapter 1.4. Finally, to determine what the outcomes of the project must be, the deliverables are determined in chapter 1.5.

1.1 Company background

Chapter goal
To understand the reasons for the project, the reader must become familiar with the current situation. The goal of this chapter is to make the reader familiar with the client company, the Accell group. Here, Accell's portfolio, assembly plant and goals are described to provide insight in the company situation.

Accell description
Accell is a mass-production company which produces bicycles under well-known bicycle brands, such as Batavus, Sparta and Koga. "Accell Group focuses on the mid-range and higher segments of the market for bicycles and bicycle parts and accessories. They are the European market leader in e-bikes and the European number two player in bicycle parts and accessories. Well-known bicycle brands in their portfolio include: Babboe, Batavus, Ghost, Haibike, Koga, Lapierre, Raleigh, Sparta and Winora. XLC is the exclusive brand for bicycle parts and accessories." (Accell, 2020)

Assembly plant
In Heerenveen, two assembly plants are present; the main assembly plant and the Koga assembly plant. In the main assembly plant, over 250 bicycle models are assembled on 7 assembly lines. These assembly lines are capable of processing multiple bicycle models. The Koga assembly plant is focussed on building high quality bicycles at medium volumes while the main plant is aimed towards the large-scale production of bicycles. To maximize the effects of the project, the main assembly plant is chosen as subject since process improvements in large-scale production influence more products. The main plant of Accell is depicted in figure 2.

Fig. 2 Accell main assembly plant in Heerenveen (Burosipma, (n.d.)).

Assembly lines
An assembly line has 16 stations where one person per station generally performs 5 major assembly operations in XXX seconds. These operations constitute of many movements per operation. Once the bicycle frame has moved through all 16 stations, it is transformed from an empty frame to a finished and packaged bicycle ready for shipment to a bicycle shop or a long-term storage facility.

Accell goals
Accell wants to reduce their production costs by improving their assembly facilities to remain competitive in the market by pursuing automation solutions.
Since Accell produces a variety of bicycles at the same assembly lines, the assembly lines must be capable to assemble many bicycle models in the same time frame. This requires the assembly lines to be flexible. The assembly stations must be able to process various materials using various assembly movements. Also, Accell is a well-known brand. Therefore, the quality of the bicycles produced at the assembly lines must also be considered while maintaining the high production rate of varied bicycle models.

Conclusion
To create a solution which is desirable for the stakeholder Accell, the conditions for the project to be desirable must be identified. This requires the identification of the elements of the assembly line that are most relevant to meet Accell's goals. To identify these elements, knowledge on how Accell's assembly lines work must be generated. This is done by analysing their most produced bicycle's assembly line as a case study. Their most produced bicycle is described in the next chapter.

1.2 ABC Model bicycle background

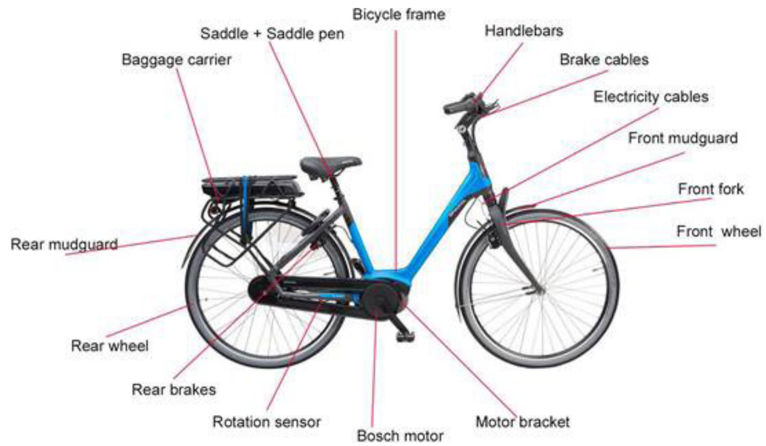

Fig. 3 Major parts of the ABC model.

Fig. 4 The electic Bosch motor of the ABC model.

Fig. 5 User display of the ABC model.

Chapter goal

The goal of this chapter is to make the reader familiar with the most produced bicycle model whose assembly line is used as case study for this project. Due to confidentiality, this bicycle model will henceforth be referred to as “ABC Model” for reading convenience. This case study aims to generate knowledge on the assembly line to determine which elements are most relevant for the improvement of the assembly line. To explain why the ABC Model is chosen as case study, the background of the ABC Model is described. Since the ABC Model bicycle is an electrical bicycle, the parts which are different from a regular bicycle are also covered in this chapter. The reader is provided with a brief description of the assembly method for this bicycle, so that the idea of the assembly line is clear before the research plan is detailed in the next chapter.

ABC Model background

The ABC Model is Accell’s most produced bicycle for 2019 and 2020. It is elected as the E-bicycle of the year by RAIvereniging (Spanninga, 2019). The bicycle is sold for €2699.- at the time of writing (Sparta, 2020), which makes the bicycle part of the high-end product range of Accell. The high price and production volume of the bicycle caused the bicycle to be chosen as case study, so that the outcomes of the investigation can affect as many bicycles as possible.

Bicycle parts

The ABC Model is an electrical bicycle. An electrical bicycle has additional parts compared to a regular bicycle; a motor, battery, display, sensors and data cables. These additional parts require additional assembly steps at the assembly line. Since this additional work costs additional assembly time, the assembly of electrical bicycles have higher assembly costs compared to regular bicycles. The motor and display are depicted in figure 4 and 5 . The ABC Model bicycle is built from 471 parts, consisting of 266 unique part types. The major parts of the bicycle are depicted in figure 3.

Assembly line

The bicycle is produced on one of Accell’s four mixed e-bicycle assembly lines, where other e-bicycles are also produced. This assembly line consists of 16 assembly stations where the individual parts are added to the bicycle frame. The assemblage of the bicycle is performed in an upside-down fashion. This makes some assembly operations easier such as feeding the wiring through the bicycle frame or fastening the motor block which can rest on the bicycle in this orientation.

Conclusion

The assembly line of this bicycle will be used to identify what assembly line aspects are valuable to improve for Accell. When these aspects are identified, the appropriate methods for the improvement of the assembly line can be identified, investigated and applied. The improvement of the assembly line requires a research plan to specify Accell’s goals and the scope of the project. The research plan is described in the next chapter.

1.3 Research plan

Chapter goal
This chapter aims to make the reader familiar with the project. To identify which conditions are required for the project outcome to be feasible and desirable, this chapter describes which problems this project aims to tackle, what the objective is and which scope this objective has. The problem description provides insight in how the original assignment was changed to the final assignment. The objective description transforms Accell's goals into tangible goals which serve as design parameters to measure the successfulness of the project to.

Project setup
The project got initiated by a collaborative project called RoboFiets between Accell, the Delft University of Technology and Chalmers University of Technology aimed to investigate the implementation of new technology to the assembly of bicycles. Examples of research topics under this project are: virtual twins, autonomous delivery robots, assembly automation and augmented reality. This project is a subcomponent of the larger RoboFiets project.

The participants of this graduation project from the TU Delft are:

- Fabian Bosman as graduating student.
- Doris Aschenbrenner as chair.
- Bas Flipsen as mentor.

The participants of this graduation project from Accell are:

- Michiel Harmsen as company coach.
- Annemarie Jorna as company coach.

Problem description
The bicycle branch is a competitive market. To gain the upper hand on the competition, Accell is investigating the improvement possibilities of their assembly hall. In cooperation with the Delft University of Technology, COMAU and Chalmers University, they aim to implement technological improvements to their assembly lines. Currently, the assembly of bicycles is manual labour. To save costs and reduce assembler workload, Accell aims to investigate the implementation possibilities of automation solutions to the bicycle assembly lines. The original assignment was to investigate the automation potential of assembly operations by analysing the Accell cargo bicycle assembly line as a case study. If automation solutions were found, they could be used for the other assembly lines as well. During a three-week visitation to the main production hall, it became clear that the cargo bicycle assembly line was not yet built. Therefore, analysis of this assembly line was not possible. In consultation with the Accell project management and project chair, the decision was made to investigate another assembly line instead, with the ABC Model bicycle as study subject.

Objective
The objective of this project is to investigate the improvement possibilities of Accell's assembly lines and to create a repeatable approach to incrementally improve the assembly lines. This would create an outcome that remains viable on the long term.
The assembly lines are to be improved on the following aspects, as detailed by Accell in the project brief (appendix A):

- Assembly line efficiency
- Bicycle quality
- Assembly costs
- Physical assembler workload
- Faulty bicycle amount

To improve the assembly line based on these goals, the individual assembly operations are targeted for improvement. Because the assembly operations require various movements to fasten 470 parts to the ABC Model frame, the improvement of these five aspects at the assembly line is a case by case process. The improvement of the assembly operations is complex in some situations since changes to these assembly operations influence others. Changing a small selection of these diverse operations would yield small returns if the solution cannot be applied to other assembly operations. Therefore, it is necessary to create a solution which can structurally improve the assembly lines by incrementally solving the various aspects of the ABC Model assembly line. This would create a solution which remains viable on the long term. The main research question therefore is:
How can the ABC Model bicycle assembly line be structurally improved in such a way that the solution is also feasible for the current and future assembly lines?

Scope
As described in chapter 1.2, the scope of this project is limited to the ABC Model assembly process since this is Accell's most produced bicycle. The ABC Model assembly is further interesting since it is assembled at an assembly line which processes other electrical bicycles. Therefore, the results of the investigation can be helpful for other assembly lines in future case studies. This assembly line does not stand alone in the process of creating a bicycle. To understand the reasons behind the current state of the assembly

line, the context of the assembly line is included in the project scope. The bicycle design department was interviewed to understand why the specific assembly materials are used and to find out which aspects of the bicycle can be changed to improve the assembly of the bicycle. The interactions between departments were investigated to understand possible causes of inefficiency. The assembly hall department was investigated to determine their influence on the assembly line's logistics and planning.
The results of these investigations were considered when proposing improvements to the assembly line to make the improvements relevant in the current situation.

To propose these improvements, the assembly line was investigated using lean practices (The lean six sigma company, 2018). Lean practices are already practiced in Accell's Koga production facility. Since a part of Accell is already successfully practicing lean practices, the application of these methods is more likely to be accepted in the assembly hall. This investigation is further described in chapter 4 and 5.

Conclusion
So far, the problem, objectives and scope are declared. To reach the objectives by solving the problems in this scope, it is necessary to identify and understand the reasons for the objectives. This provides clear insight in the current situation, which outcome would be desirable for Accell and the reasons for Accell's goals. The research questions which investigate the current situation within the project scope are described in the next chapter.

1.4 Research questions

Chapter goal
To propose desirable improvements to the assembly line, the goals which this project works towards are investigated. This chapter describes which questions were identified to be relevant for the report aims to answer, and which information was collected and analysed to understand the situation.

Main research question
The main research question which is answered in this report is:
How can the ABC Model bicycle assembly line be structurally improved in such a way that the solution is also feasible for current and future assembly lines?

This goal is subdivided into the various improvement goals of Accell to make it possible to focus on the individual elements of the investigation.

Research questions and sub research questions
To understand how the goals can be met, the reasoning for the goals is questioned using the research questions depicted in figure 7.
To make these broad research questions manageable, they are divided into smaller sub-research questions. These sub-research questions are aimed to understand Accell's current situation, what the optimal situation could be, why the current and optimal situation differ and how the current situation could be changed into the optimal situation. These research questions will help to establish the requirements to answer the main research questions. They will be answered using multiple investigation techniques in chapter 2.5: Assembly line performance.

Fig. 7 Accell's goals converted to research questions and sub-research questions.

1.5 Deliverables background

Chapter goal
The investigation leads to multiple outcomes that must be useful for Accell and the scientific community. This chapter describes what would be desirable deliverables for the outcomes of the project.

Deliverables
This project aims to provide three deliverables:
1. A method which allows the investigator to determine the largest assembly time reduction opportunities and structurally generate improvements.
2. An overview of the ABC Model assembly line detailing the improvement opportunities.
3. A multitude of ideated and tested improvements for the largest time reduction opportunities.

Deliverable 1
The first deliverable, the method, is useful for Accell to structurally reduce assembly time and improve the assembly line situations. It could for instance be used for future investigations and assembly line improvement experiments. This deliverable would provide a solution which remains viable on a long-term scale, since it can be structurally applied.

Deliverable 2
The second deliverable of the opportunities overview is useful for Accell to focus these future investigations on the assembly line aspects with the largest potential impact. This deliverable would provide the Accell stakeholder an overview which can be directly used for further assembly line investigations.

Deliverable 3
The third deliverable of the tested improvements can be implemented by Accell to already reduce assembly time and assembly line workload. This deliverable aims to provide Accell solutions which can be feasibly implemented in the current situation.
These deliverables are presented throughout the report.

Overview of future chapters

Chapter 2 covers the current state of the assembly line.

In chapter 3, the literature used to create a viable method for deliverable 1 is presented.

In chapter 4, the process of developing this improvement method is displayed. The realignment of the tools based on the found information during the project is also described here.

In chapter 5, the assembly line improvement method is presented, and the choice of methods is justified.

In chapter 6, The method is tested in three assembly line situations to test the viability of its long-term applicability.

In chapter 7, the results from these three tests and the collected knowledge of the assembly line are discussed to provide insight on the assembly line situation and the possibilities of improvement.

In chapter 8, conclusions from these investigations are drawn and the feasibility of the method is compared to the project goals which are translated into evaluation criteria.

Chapter 9 provides discussion on what could have been done better during the project and what remains to be investigated based on this investigation. In the next chapter, information on the current situation is gathered.

2. Overview of the current situation

The goal of this chapter is to provide insight in the assembly line. This is done by detailing the individual assembly stations to create a broad understanding of what happens at the assembly line. To further understand the assembly line, the context of the assembly hall is also described to create insight on the influence of the other departments on the assembly line operations. This knowledge was collected using various analysis methods. Since the assembly hall is a complex system where many departments interact, context mapping was applied to understand the interdepartmental influences. To understand the social situation of the assembly line and to gain information on specific topics, semi-structured interviews were used. The assembly operations of the assembly line were captured on video for analysis.

Understanding of the ABC Model assembly was gained using guided bicycle assembly. This method entailed the dis-assembling and re-assembling an ABC Model bicycle together with an expert. To gain understanding of the practical situation at the assembly line, hands on experience was gained by working at the assembly line at various stations. These methods were applied to identify which elements were relevant for the project to investigate and which problems must be tackled in the project.

In this chapter, these measurement methods are described, and the outcomes of these measurement methods are detailed to create understanding of the current state of the assembly line.

Chapter goal
To prepare for the application of improvement methods, the current situation of the assembly line is detailed. In this chapter, the individual parts of the assembly line are detailed to make the reader familiar with the assembly process at the ABC Model assembly line.

Assembly line stations
Accell uses linear assembly lines to produce either multiple electronic-bicycle types or multiple regular bicycles per assembly line. The ABC Model bicycle is assembled at an electronic-bicycle assembly line. As can be seen in figure 8, this assembly lines consist of four parts; the preassembly, manual assembly line, powered assembly line and testing & packaging.
At the assembly line, all 16 assembly stations contain one worker. One assembly line leader ensures that the assembly line production operates as desired. At the first two stations, operations are performed which are easier to do if the bicycle frame is unattached to the assembly line such as fastening the handlebars or attaching the front fork. The bicycle frame is then placed on the manual assembly line (station 3 to 6). Here, operations are performed which vary in assembly time such as inserting cables at station 3 or attaching the brakes. At the end of the manual assembly line, the bicycle frame is lifted and moved to the powered assembly line. At this powered assembly line (7 to 14), operations are performed which have more stable time spans. The cycle time of the assembly line is XXX seconds. After this time frame, the powered assembly line pulls the bicycle forward to the next station. After leaving the powered assembly line at station 14, the bicycle is moved to the testing and packaging area. Here at station 15 and 16, the bicycle's electronics are tested, and the bicycle is packaged. The warehouse department then moves the bicycle to a transfer area where it is transported to a warehouse or bicycle store.

To make the reader more familiar with the assembly stations, the following chapters detail the stations in more detail. The overview of the assembly line tasks was created by capturing all assembly stations on camera and analysing the video footage.

The analysis of the video footage is further described in chapter 4: Ideation.

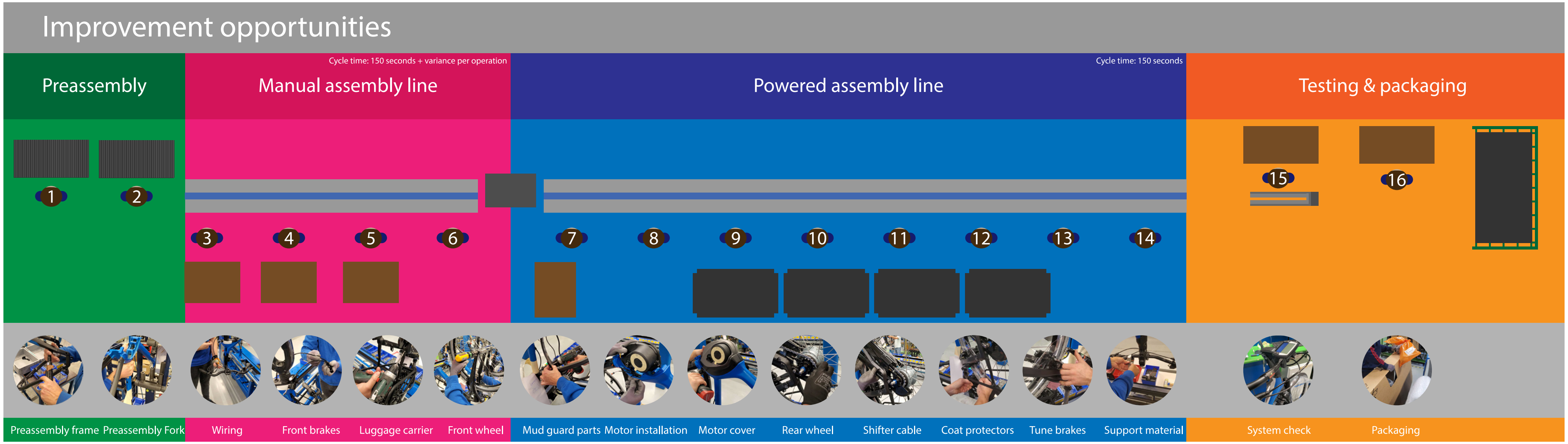

Fig. 8 Top view of the assembly line.

2.2 Preassembly stations

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2.3 Manual assembly line

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2.4 Powered assembly line

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2.5 Testing & packaging

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2.6 Assembly line in context

Now that the assembly operations are known, the other relevant aspects of the assembly line are described. This chapter details the influences of the other departments on production of a bicycle and the influences on the assembly line itself. Since the other departments influence the assembly line, it is interesting to determine what these influences are. This would provide the opportunity to cooperate with other departments to improve the assembly line. These other departments were investigated by performing context analysis and interviews, see chapter 2.7. These gave insight on the origin of assembly problems and the design cycle of bicycles at Accell.

First, the flow from bicycle conceptualization to sales is investigated, figure 9. Then, the most relevant assembly line departments are investigated such as the design department which defines which materials and assembly operations are required and the warehouse, preassembly and sub-assembly departments which provide the materials to the assembly line. These various departments and employees have different goals to achieve. These goals are further investigated to understand how the current assembly situation was created. The goals are presented in figure 10. Here, the stakeholders are not aligned on a common goal.

The design department, paint shop and sales department aim for customer satisfaction while management, sourcing and assembly line leaders aim to produce large volumes of bicycles. This difference in goals causes a situation in which bicycles optimized for customer satisfaction must be produced in large volume. Since the production in large volumes is not a main concern in the design department, the bicycles are not optimized for large production by using design for assembly principles. This makes the assembly of the bicycles inefficient. The influence of the production cycle and stakeholders are described on the next page.

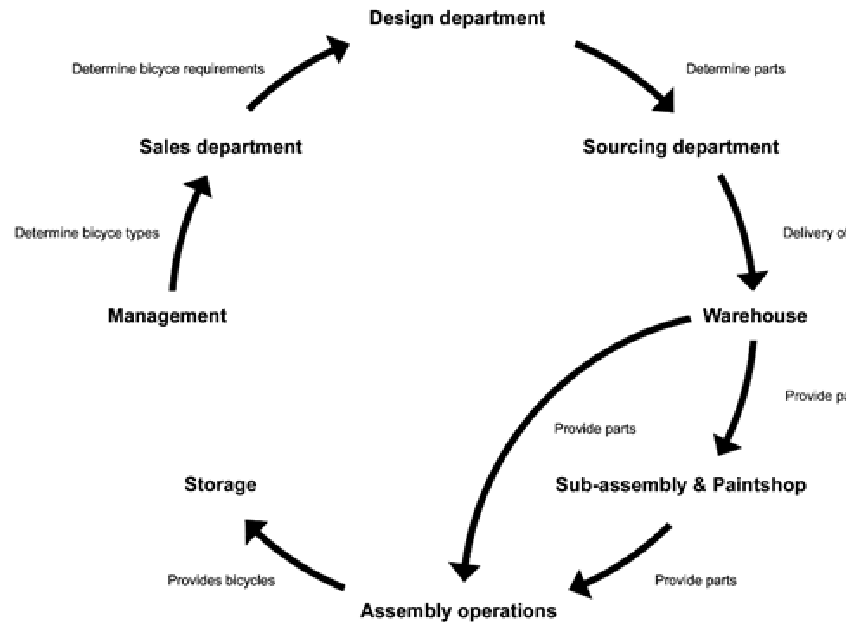

Fig. 9 Production cycle of a bicycle at Accell.

Management Increase revenue. Sell as many bicycles as possible.	**Sales** Make bicycles which customers will purchase. Integrate in bicycles: - New designs - Customer experience - React to competition - Integrate new technology	**Designers** Design bicycles with these aspects: - Safe - Beautiful - Functional	**Sourcing** Aquire required materials. Plan the production to conform to the requested production volume.
Assemblers Perform my assembly steps. Keep my job.	**Line leaders** Meet production volume targets.	**Paintshop** Provide great paint quality. Improve the painting process. Innovate paint qualities & types.	**Warehouse** Organize and deliver parts to the assembly lines and paint shop an hour in advance.

Fig. 10 Overview of stakeholder goals.

Influence design department

A semi-structured interview was conducted with the design department leader to investigate the influence of the design department to the assembly of the bicycle. This made the goals and influence of the design department related to the assembly line clear. The design department aims to make safe, beautiful and functional bicycles. Design for assembly is not a point of focus. Since the design department determines from which materials a bicycle is produced, which connections are used to assemble the bicycle and where these connections are located, the design department has a large influence on the assembly operations. As a result the bicycle models are now hard to assemble. But, this influence on the assembly operations could potentially be leveraged to make assembly operations easier and more efficient by communicating with the design department to implement design for assembly practices. Therefore, cooperation with the design department to improve the assembly line is viewed as a possible way to improve the assembly lines.

Influence warehouse & paint shop

To investigate the logistics relevant to the assembly line, the department leaders of the warehouse, paint shop and day planning were interviewed using the semi-structured interview method. The warehouse and paint shop prepare and deliver the materials to the assembly lines, as depicted in figure 11. To ensure assembly line uptime, the required assembly materials are made known to the warehouse department based on a day to day planning. The day to day planning itself is based on the available materials and painted frames. From this day-planning, the warehouse department has one hour before the production of the bicycle production runs to provide the required materials to the assembly line. Before the materials are provided to the assembly line, the warehouse department unboxes the materials so that the assembly line does not have to open packaging. If a lack of materials is spotted at the assembly line, the warehouse department is notified, and the shortages are filled as soon as possible. According to the warehouse, the accuracy of their deliveries is higher than 99%. This provides solid grounds for assembly line improvements, since rationalisation starts with adequate supply chain & material quality (Nof, 1997, p. 22).

Furthermore, the bulk materials on the assembly line are often in front of the assemblers while the larger materials are filled behind the assemblers, which allows the warehouse department to deliver the assembly materials without obstructing or disturbing the assembly process. Since the provision of material is performed in this way, changes in assembly station layout to lower assembly times must be communicated with the warehouse department to ensure that the assembly is not obstructed during material refilling.

Influence sub-assembly department

The sub-assembly departments simplify the work at the assembly line by assembling bicycle parts into easier to assemble sub-assemblies which are provided to the assembly line. Examples of these sub-assemblies are the handlebars, the front and rear wheels and the luggage carrier. Since these departments influence the required activities at the assembly line, communication with the sub-assembly departments could potentially improve the assembly line operations.

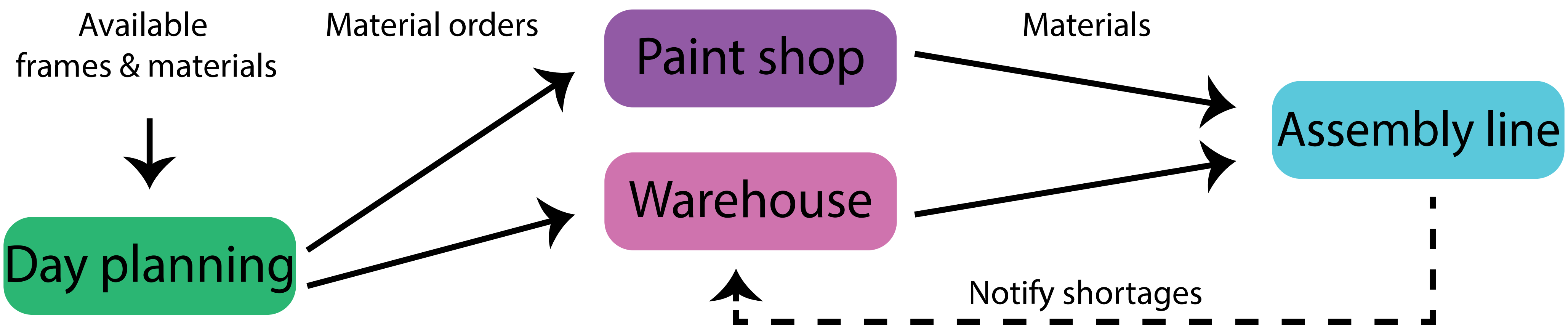

Fig. 11 Information flow of assembly hall logistics.

Chapter goal
To provide insight on how the assembly line performs, the methods context mapping, interviewing, data centric design, expert guided bicycle design and hands on assembly work experience were used.

Context mapping
"Context mapping is a procedure for conducting contextual research with users, where tacit knowledge is gained about the context of use of products." (Visser & Stappers, 2020). By immersing into the Accell assembly hall, taking tours through relevant departments guided by the department responsible, working together with assemblers, speaking to all kinds of personnel and department heads, it was possible to get an understanding of the assembly hall situation from multiple perspectives. This was done to gain an unbiased view of the assembly situation.

Semi-structured interviews
To gain insight in how the assembly hall operates and how the different departments communicate, semi-structured interviews were conducted. These provided the necessary insight to provide a clear overview of the company structure and culture. The interviewees were the lead designer, warehouse department head, paint shop department head, repairmen, various assemblers and planners. A semi-structured interview is described as "A semi-structured interview is open, allowing new ideas to be brought up during the interview as a result of what the interviewee says. The interviewer in a semi-structured interview generally has a framework of themes to be explored." (Edwards & Holland, 2013)

Data centric design
Data centric design was used to produce quantitative data to understand and de-construct the assembly line operations into analysable movements. The quantitative data produced complemented the qualitative data gained from context mapping and semi-structured interviews. The data was gathered by recording all 16 assembly line stations on video. From the video footage, the balancing of the assembly lines was determined. This was investigated by comparing the cycle times of the individual assembly stations to the whole assembly line cycle time.

Another application of the video footage was to determine which assembly operations could be improved. Possible problems could emerge by the confidentiality of the collected data, this was discussed with Accell at arrival. To allow revisiting the data at different stages of the project, the assembly line operations were recorded on video. The video footage collected from this project provided a valuable contribution to the framing EIT project context, because due to the Covid-19 outbreak the researchers have not been able to conduct first-hand research on the production line but used the recorded video footage instead.

Guided bicycle assembly
Disassembling and reassembling a bicycle together with an expert produces tacit knowledge on the assembly steps, understanding how the different assembly steps influence the assembly order and understanding of the influence of the bicycle design on the assembly line steps. Therefore, we expect to find useful insights on how the assembly line environment is shaped by the products it produces. An example of the expert guided disassembly is presented in figure 12.

Hands on assembly work experience
The assembly line operations must be thoroughly understood to provide meaningful improvements. Practical experience of the assembly line operations provided insight on the meaning of the collected video data. The practical experience was gained by performing manual work at the assembly stations with the goal of learning to complete the assembly operations in the same time frame which the assembly workers have available (XXX seconds). This provides insight in the real situation and the problems originating from this specific practical situation which elude the managerial plans, literature and conversation. Working at the assembly line created trust between the assemblers and the researcher. This created opportunities to converse at ease, improving the quality of the context mapping.

Fig. 12 Guided bicycle disassembly.

Chapter goal
The investigation of the assembly line is described in the previous chapter. The goal of these investigation methods was to gather knowledge on which elements of the assembly situation are most relevant for the improvement of the assembly line. This investigation also aimed to create insight on the complex situation of the assembly hall by creating focus on the most relevant assembly line aspects.

Context mapping
The context mapping investigation increased the understanding of how the assembly hall worked. The most important findings from this investigation are highlighted here.

Interdepartmental communication could be improved
During a tour of the assembly hall and in conversations with the planning department, it was explained that the day-to-day planning of the assembly line was dictated by the capacity of the paint shop to paint parts and their capacity to change colours between bicycle models. For the assembly line, this meant that the allocation of bicycle models for assembly was based on the available painted materials. This resulted in limited planning possibilities and allocating a mix of bicycle models to the assembly lines to keep them running. During the paint-shop tour, the opposite was explained. The paint-shop was not running at full capacity. Instead, it was running at low capacity due to the limited knowledge on which bicycle parts had to be painted at what time. The result was that the assembly line and planning department incorrectly viewed the paint-shop as the bottleneck of the assembly process. Therefore, the actions of the other departments were tailored to the paint-shop, which complicated the bicycle model mix and scheduling for the warehouse department and assembly lines. This perceived discrepancy evoked further investigation on the interaction between departments.
When the department head was asked about the preparation for materials before transfer to departments, it was told that there was limited communication on how these materials could be optimized for the other department. Instead, both departments did what they thought was best for the other department. This resulted in deliverables which are not optimized for other the other departments, since problems with the delivered materials are not communicated to the previous departments in the process.

As example, the situation in figure 13, is used. At the assembly line, bicycle frames have threaded holes where bolts can be fastened to. It commonly occurs that these bolts do not fit in the threaded holes, due to low quality threading or paint residue. To correct the threading, the assembly department re-tapers these holes. At the paint-shop or frame preparation department it is not known that this re-tapering occurs. If they would know that this correction occurs, they could eliminate the need for this correction by for example plugging the threaded holes. The paint shop already plugs other holes of the bicycles since they found paint residue in the holes. These re-tapered holes of the ABC Model frame could be included as well. Instead, it was observed that the assembly department keeps correcting the situation instead of communicating to these departments and structurally eliminating the problem. Therefore, the usage of interdepartmental communication to solve assembly line problems must be considered for the structural improvement of assembly line issues.

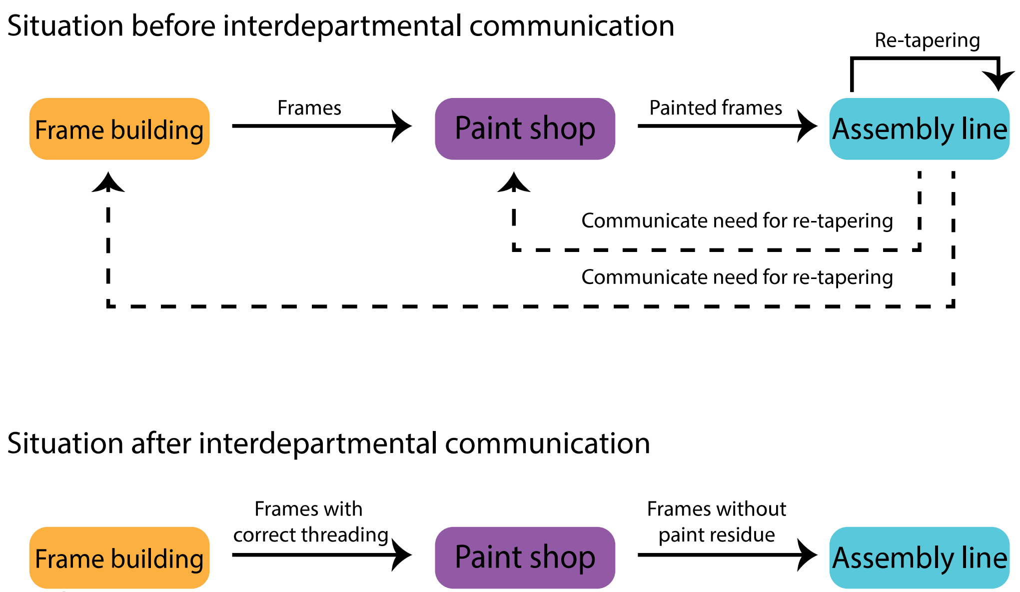

Fig. 13 Communication to eliminate re-tapering.

Origins of damages are not tracked
During the investigation of the assembly line, stickers on bicycles were noticed. If damages at the assembly line are found, a sticker is attached to the bicycle. This sticker does not indicate where the damages originate from. After this sticker is placed, the assembly process is continued. Once the assembly process is complete, the bicycle is sent to the repair department for disassembly. This approach has two results: the origins of the damages remain unknown. Therefore, these origins cannot be investigated and be changed to ensure that the damages do not reoccur. The other result from this approach is double work for both the assembly line personnel and the repair department personnel. If the bicycle would not be completed after finding damages, there would be no need to disassemble the whole bicycle. This leads to less required work for the assemblers (performing all the assembly steps after the damages is found) and less work for the repair department (undoing all assembly steps after the damages are found). These findings indicate that setting up a structure to find the causes of damages can be beneficial in the prevention of the damages. Therefore, structurally searching for damage causes is considered during the project.

Possibility for capitalization of assembler creativity
During visitation of the assembly line, conversations were held with the assemblers. When the assemblers were asked for suggestions to improve the assembly line process, multiple ideas were provided such as the placement of protective material on the finished bicycle rack to avoid scratching during bicycle transport.
According to lean methodology, employee talent is often underutilized (The lean six sigma company, 2018). Since the assemblers have expertise on the assembly of bicycles, this experience can possibly be applied to tackle assembly line problems by providing meaningful improvements to the assembly line.

Semi-structured interviews
Semi-structured interviews were applied to better understand the complex interactions between the various departments by discussing what the departments viewed as important and how things worked on practical level.

Assembly line production rate
To gain a better understanding of the assembly situation, the assembly line leaders were interviewed. Here, it became clear that an assembly line on average produces XXX bicycles per day. The average time to complete the assembly of a bicycle through all 16 stations is XXX minutes. These numbers provide a baseline to which the outcomes of the assembly line video analysis can be compared.

Lack of design for assembly practices
The design department head was interviewed to gain insight on the design process and the priorities for the design of a bicycle. This department head stated during this interview that the focus of the design process is on “Safety, beauty and functionality”. The assembly of the bicycle is not a “driving factor” according to this interview. Since the optimisation of the bicycle designs for assembly is not a priority, there is limited on design for assembly. By making the assembly of the bicycle a priority for the design process, there is potential for assembly line improvement. This will be considered during the investigation.

Large part variety
The interview with the design department head also resulted in the insight that a large variety of parts was used across the bicycle models for the same function. “The parts are selected based on what fits best for the customer experience”. This selection is then compared to the possibilities from the acquisition department to determine which parts can be purchased. To save time, the parts which are estimated to have a low chance of not fitting are ordered in advance. This selection of various parts for similar assembly situations leads to a large variety of bicycle parts across assembly operations and bicycle models. Since this part variety is large, possible automation solutions must be able to handle various materials. This increases the cost price of automation of the assembly process, since the automation solutions must be more lenient (Nof, S. Y., Wilhelm, W. E., & Warnecke Hans-Jürgen, 1997).

Variance of tolerances of frames
During an interview with the department head of the frame building department, it became clear that the size of the bicycle frames differed per purchased batch. The bicycle frame generally differs 1 mm per pipe of which the frame is built. This means that the location of the threaded holes and other bicycle features can differ up to 4 millimetres per bicycle. For manual assembly, this is not an issue since the assembler does not notice a location change of a few millimetres. An automated solution, however, would notice these differences and would require sensors to adjust for these location changes. This variability of tolerances provides a hurdle for the implementation of automation since sensors for correction are required. This makes the implementation of the automation more expensive, since sensors will have to be purchased, calibrated and programmed to correct the movements of the actuator (Nof, S. Y., Wilhelm, W. E., & Warnecke Hans-Jürgen, 1997).

Data centric design
The assembly line was captured on video for analysis. The analysis of the video footage is further used in chapter 4 and 5. Here, other observations from the assembly line footage are described.

Assembly materials are located behind the assembler
The large assembly materials are placed on racks and material holders behind the assembler on the assembly line. This makes the provision of assembly materials easier for the warehouse department. This placement also causes the need for the assembler to turn to gather materials for an assembly operation. The smaller bulk materials are placed in front of the assembler, closer to the assembly location. The consequent need to turn for materials seems to cost additional assembly time. This assumption is a point of interest to investigate whether the assembly line layouts could be improved.

Non-ergonomic operations are observed at the assembly line
During the video capturing process, multiple cases were observed where an assembler must lift the bicycle frame with materials attached; at station 2 and station 6. At station 14, a special machine is used to avoid lifting the heavy bicycle. At these two stations, however, the lifting is required. This heavy operation seems to be non-ergonomic in nature. Based on this observation, the ergonomic aspects of the assembly line become a point of interest for the investigation.

Expert guided bicycle disassembly
Together with an expert bicycle repairman, the ABC Model bicycle was disassembled and reassembled to create insight on the practical level of the assembly process. This provided the following relevant findings:

The fastening locations are often placed in hard to reach locations.
During the reassembly of the bicycle, it became clear that the fastening locations of multiple materials were hard to reach. Fastening the cable guide on the rear mud guard required the assembler to assemble in an awkward stance. It also occurred multiple times that access to a threaded hole for a bolt was blocked by other materials or geometry of the bicycle frame. Fastening then required screwing at an angle, which potentially leads to incorrect fastening of the bolts. These findings led to the suspicion that the bicycle design could be optimized for assembly. This strengthened the same finding from the semi-structured interviews. Therefore, considering the implementation of design for assembly practices for the bicycle becomes more promising.

Assembling the ABC Model bicycle requires complex tool movements, which causes scratching.
Dis-assembling and re-assembling made it clear that multiple assembly operations require the assembler to orient and rotate tools in an awkward pose or tool orientation. During these operations, the tools must not touch the lacquer of the parts or frame. If the tool touches these parts, a scratch is made on the surface. If the scratch is not too severe, the bicycle can still be sent for transport. If the scratch is severe, however, disassembly and replacement of the damaged parts is required. If the bicycle frame is scratched, the whole bicycle must be disassembled. Due to the amount of repair and rework from the 7 assembly lines, three expert assemblers work full time to manage the damages from the assembly line in the low season. Avoiding scratches to increase the quality of the produced bicycles is interesting to the project since a scratch is easy to make when complex tool movements are required.

Hands on assembly work experience
The hands-on experience gained at the assembly line provided insight in how heavy assembly operations were to perform and how hard they were to perform under time pressure. The findings from the hands-on experience were consistent with some of the findings from the other investigations. The need to re-taper holes due to paint residue, low-quality materials or incorrect fastening handle was experienced first hand when a hole required re-tapering after a bolt was incorrectly aligned and fastened. It further confirmed that there is a possibility to capitalize on the assembler creativity. During conversations with the assemblers while performing the assembly operations, it became clear that the assemblers proposed multiple improvement ideas when asked. Performing the assembly operations under time pressure also made it clear that bicycle designs made it hard to reach assembly locations. Reaching the assembly locations within the time limit was hard to do, due to the often complicated movements required for assembly. The last aspect which was confirmed was that the assembly materials are located behind the assemblers. This material position required many turns and reaching motions to gather the materials for assembly operations. For the design of the assembly line improvement method, it is relevant to include these aspects in the investigation.

Conclusion
Based on these findings from the investigation of the current situation of the assembly line, the research questions and sub-research questions can be answered. The findings from the current situation investigation are clustered per research question and sub research question in the next chapter.


Fig. 14 Assembly materials behind assembler.

2.9 Context analysis outcomes

On the following pages, the results of the multiple context analysis methods are presented. These results answer the sub-questions that were described in chapter 1.4 research questions. The findings are categorized per research question. The findings per category are used to create a list of requirements to which an assembly station is compared to find out which aspects can be improved, see chapter 3.7 for the list of requirements.

Improve assembly line efficiency
The findings from the video analysis, interviews, observations and hands on experience are described in the figure which is removed due to confidentiality below. The answers to the current efficiency of the assembly line, 47%, indicates that there are opportunities to improve the situation. Simple and plausible improvements are provided by the personnel during conversation and low hanging fruit improvement opportunities are observed at the assembly line such as changing the layout of the materials to decrease time spent on walking to the materials. The reasons why the current assembly line is not maximally efficient yet range from not communicating improvement opportunities to other departments to the lack of design for assembly practices by the design department. The optimization of the assembly line can be found in these opportunities by implementing design for assembly practices (Apple, 1972) or reducing material variety across bicycle models (Yoshimura, 2014). The findings from the sub-questions provided further insight in the assembly line situation and provide direction for the assembly line improvement efforts in chapter 4 and 5.

Due to the confidential nature of the context analysis results, they are removed from the public version of the report. In the confidential report, the research questions are answered here, and support for the claims above are provided.

Improve bicycle quality

The current state of the bicycle quality was investigated by observing the assembly hall, interviewing the bicycle repairmen where damaged bicycles are brought to be disassembled. Accell's assembly lines use a stickering system to indicate if a bicycle is damaged. After the bicycle damage is indicated, the bicycle's assembly continues until the bicycle is complete. Once it is complete, it is brought to the repair department. The repair department then breaks down the whole bicycle in case of a damaged frame, and rebuilds the bicycle using a new frame. Such activities require unnecessary time to perform, since finishing the damaged bicycle's assembly will get undone by the repairmen. The sticker system also does not indicate where the origin of the damage is, so no investigation of where the origin of damaged bicycle parts is can be performed. Other observed quality issues at the assembly line are re-tapering of fastening holes due to the use of low-quality materials or low-quality tapering. These observations provide opportunity for improvement, by implementing design for assembly practices, eliminating the origins of ill-tapered holes and establishing a system which tracks the source of damages to the bicycles. The overview of the current state, perceived possible quality, reasons why the bicycle quality is not at its maximum and proposals to improve bicycle quality are depicted in the confidential figure below.

Due to the confidential nature of the context analysis results, they are removed from the public version of the report. In the confidential report, the research questions are answered here, and support for the claims above are provided.

Lower assembly costs
The assembly costs are tied to the assembly time of the bicycles. Since the current assembly costs are sensitive information, they cannot be shared in the report.
The assembly costs are not at their minimum due to the 47% efficiency of the assembly line. This means that half of all time spent on assembly does not contribute to changes of the bicycle. By increasing the effectiveness of the assembly line, more bicycles can be produced in a shorter time frame, lowering the assembly costs per bicycle.
Furthermore, hands-on experience at the assembly line showed that the current assembly operations are often complicated operations and the assembly locations are hard to reach. The assembly line efficiency can be improved by reducing bicycle assembly operations variety, reducing bicycle variety (Nof, S. Y., Wilhelm, W. E., & Warnecke Hans-Jürgen, 1997) and simplifying assembly operations (Apple, 1972). The overview on the findings of the sub-research questions is provided below in the confidential figure below.

Due to the confidential nature of the context analysis results, they are removed from the public version of the report. In the confidential report, the research questions are answered here, and support for the claims above are provided.

Reducing physical workload of the assemblers
Because the assembler has XXX seconds to perform several actions at the assigned station, the possible improvements must not increase the amount of actions as assembler has to perform. Improvements which take the workload of the assemblers into account and at least not increase this workload are preferred. Next, from interviews with the design department it was found that the ergonomics during assembly are not taken into consideration when designing the bicycle. To at least not increase the workload for the assembler the ergonomics of the tasks should be considered when proposing changes to e.g. the location of the materials. The overview of the sub-questions related to the reduction of physical workload of the assemblers can be read in the confidential figure below.

Due to the confidential nature of the context analysis results, they are removed from the public version of the report. In the confidential report, the research questions are answered here, and support for the claims above are provided.

Reduce faulty bicycles amount
The current number of faulty bicycles requires three full-time, skilled assemblers to perform repair. The observed reasons for the number of faulty bicycles are, scratching due to required complex movements during assembly, mistakes during part assembly and use of faulty materials. These aspects are already covered in the page on improving bicycle quality. Proposed improvements to minimize these faulty bicycles are to log the origins of damage and to structurally eliminate the sources of damage to the bicycles. Another improvement could be to design the bicycles in such a way that the assembly operations are simple and minimize the chances of scratching the bicycles with tools. The overview of the sub-questions related to the reduction of faulty bicycles can be read in the confidential figure below.
These answers to the research questions and sub-research questions provide insight on what assembly line aspects are important to improve and which methods could be applied to improve these aspects of the assembly line.

Due to the confidential nature of the context analysis results, they are removed from the public version of the report. In the confidential report, the research questions are answered here, and support for the claims above are provided.

Project description conclusion
This chapter has provided insight in what the current state of the assembly line is, which aspects of the assembly line are relevant to analyse and improve, and created insight on the situation in which the assembly line is situated. The following chapter will detail the investigated literature, describing the found methods to analyse the current assembly line for improvement opportunities and to propose and measure improvement proposals.

3. Theoretical background

Introduction	Situation	Theory	Ideation	Concept	Testing	Results	Conclusion	Discussion
1	2	3	4	5	6	7	8	9

In chapter 1 and 2, the goals for the assembly line and the current state of the assembly line were detailed. In this chapter, the required knowledge for improving the assembly line towards these goals is explained. The theories described in this chapter support the analysis of the assembly line and ideation of assembly line improvements. To perform these steps towards assembly line improvement, lean practices (The lean six sigma company, 2018) are implemented. In chapter 3.1, the philosophy behind the lean methodology is detailed to provide insight in what the methodology is trying to achieve and what the ideal situation would look like. Then, chapter 3.2 details how the largest improvement opportunities can be found by categorizing the video footage using the Toyota Production System. This chapter is followed by chapter 3.3, where the MOST system is used to clearly define the performed movements of assemblers. The MOST system is also applied to estimate the required time to perform these movements. Once the movements are defined, they are compared to a list of requirements to determine what aspects of the movements are sub-optimal. The origins of this list of requirements is detailed in chapter 3.4. The next step is to determine the root causes of these unmet requirements. The method applied for this goal is the Toyota root cause analysis method "the 5 whys", which is described in chapter 3.5. This method is used to find the origins of observed assembly line problems quickly. To clarify the impact of proposed improvements, the spaghetti diagram method (Allaboutlean, 2015) is applied. This visualisation technique is presented in chapter 3.6. In chapter 3.7, the process of line balancing is described, which can be used to improve the assembly line efficiency. These methods will be used for the final assembly line investigation method, which is described in chapter 5.

Improvement philosophy (Ford, Toyota and lean methodology)
To provide background information on the methodical improvement of assembly lines, the early stages are briefly described to provide insight on the philosophy behind assembly line improvements. At the early stages of improving assembly lines, Henry Ford aimed to minimize the waste of materials and manpower: "I have striven toward manufacturing with a minimum of waste, both of materials and of human effort, and then toward distribution at a minimum of profit, depending for the total profit upon the volume of distribution." (Ford & Crowther, 1923, p. 19). Other sources of waste Ford lists are excess of force, material usage, movements and weight of objects. A problem the production facilities faced was the lack of logical arrangement of goods, causing the need to walk for materials; "The undirected worker spends more of his time walking about for materials and tools than he does in working; he gets small pay because pedestrian-ism is not a highly paid line." (Ford & Crowther, 1923, p. 80).

Since Ford, the next steps towards systemic improvement came from the Toyota Production System (Taiichi, 1988, p. 15). In this book upon which the lean methodology is based, the author provides a clear image on what to improve: "All we are doing is looking at the time line," he said, "from the moment the customer gives us an order to the point when we collect the cash. And we are reducing that time line by removing the non-value-added wastes.". This view on improvement indicates that the scope of improvement is applicable for all aspects of assembly operations.

In the Accell situation, the minimization of material and manpower for assembly operations is still relevant for improving assembly lines since manual labour is mainly used for the assembly of the bicycles. The techniques presented in the following chapters are aimed towards the minimization of the required assembly time and worker effort or creating a way to communicate these efforts.

Conclusion
The philosophy for assembly line improvement is used to guide the prototyping of a method in the direction of reducing assembly time and improving the other aspects of the assembly line through the removal of non-value-adding activities.

3.2 Toyota production system work categorization

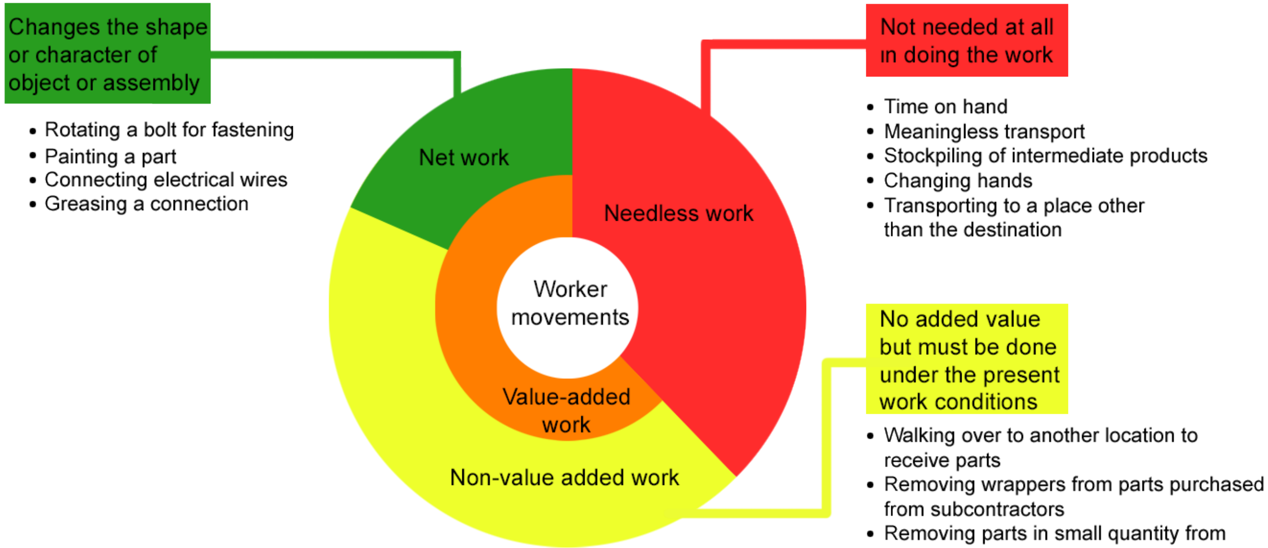

Fig. 15 Division of work (Taiichi, 1988).

Chapter goal
To determine which movements must be focused on, a distinction must be made between which movements are already as desired and which must be improved. To categorize movements at the assembly line, the Toyota Production System's work categorization (Taiichi, 1988) is applied. The Toyota Production System makes a distinction between three types of work: 1) Work which consists of waste and 2) work which is needed. The needed work is further subdivided into 2a) value-added work and 2b) non-value-added work. The definitions provided by the Toyota Production System are described in figure 15.

Waste
Taiichi describes waste as the following:
"Waste - The needless, repetitious movement that must be eliminated immediately. For example, waiting for or stacking sub-assemblies." (Taiichi, 1988, p. 61)
Other forms of waste are:

- Waste of overproduction
- Waste of time on hand (waiting)
- Waste in transportation
- Waste of processing itself
- Waste of stock on hand (inventory)
- Waste of movement
- Waste of making defective products

Non-value-added work
Non-value-added work is defined by Taiichi as:
"Non-value-added work may be regarded as waste in the conventional sense. For example, walking to pick up parts, opening the package of goods ordered from outside, operating the push buttons, and so forth are things that must be done under present working conditions. To eliminate them, these conditions must be partially changed." (Taiichi, 1988, p. 15) This means that the difference between waste and non-value-added work is that non-value-added work still has to be performed and can be minimized while waste does not need to be done at all and can be eliminated.

Value-added work
Value-added work is described by Taiichi as:
"Value-added work means some kind of processing - changing the shape or character of a product or assembly. Processing adds value. In processing, in other words, the raw materials or parts are made into products to generate added value. The higher this ratio, the greater the working efficiency." (Taiichi, 1988, p. 15) The value-added work must be performed to finish the product. The additional movements based on the situation are added to this work, which is the non-value-added work. In the ideal situation, only value-added work would occur while no non-value-added work or waste would occur. In practice, value-added work occurs due to limitations of the situation, but can be minimized. The division of worker movements is described in figure 15.

Since the project scope is limited to improvements of the assembly operations, the distinction used for the analysis of the assembly line movements is between value-added work and non-value-added work. The wastes of overproduction, transportation, processing itself, stock on hand and making defective products are solvable on a managerial level, which is out of the scope of the project. It is important to note that the value-adding work itself can be more time consuming than that it needs to be. Therefore, it is necessary to stay vigilant for improvement opportunities for work which is categorized as value-adding.

Conclusion
The division of assembly work into the categories of non-value-added work and value-added work can be applied for the assembly line analysis. It can be used to create insight on what can best be improved and to create an overview of how efficient the current assembly line is. The division must be considered with care, so that possible improvements for work which is considered value-adding are not lost.

3.3 MOST system analysis

Chapter goal

To analyse the movements of the assembly line, the MOST system analysis (Zandin, 2003) can be used. The goal of the MOST system is to minimize the time spent on analysing assembly line footage. The MOST system achieves this by estimating the time required to perform operations by coding the performed movements into specific categories. These categories are then scored on a lookup table as can be seen in figure 16. This results in a reference time. The process MOST uses to turn movements into time estimations is described below (Zandin, 2003). The advantage of using reference times from the lookup table is that only one sample is required to determine the movements, instead of processing multiple measurements to find the accurate assembly times.

First, the movements are described according to the MOST standard in this sequence:

[Gain control][Object][From location][Placement][To location]

For example:
An operator grasps his weld helmet within reach and puts it on his head.

Is described using the standard description as:

[Grasp] [weld helmet] and [put on] [head].

The next step is to score the sequence of movements according to the relevant lookup table in the corresponding movement sequence, see figure 16 and 17.

A1 B0 G1 A1 B0 P1 A0

To determine the estimated time required to perform the sequence of movements, the total of the found values is multiplied by 0.36 to gain the time in seconds:

1 + 0 + 1 + 1 + 0 + 1 + 0 = 4

*40 * 0.36 = 1.44 seconds.*

The application of MOST allows fast assembly time estimations for the analysis of the video footage. For certainty, the exact time spent per movement is also measured.

Conclusion

Since the assembly line only processes the ABC Model bicycle for a limited amount of time, and the assembly process must be hindered as little as possible, it was only possible to record one sample of all assembly operations of the 16 assembly line stations. Therefore, the MOST analysis becomes valuable to extract relevant data from a limited sample size. However, since the MOST analysis method uses standardized times, there is the possibility that the analysis differs from the actual assembly times. This must be considered during the application of MOST. Therefore, the video footage is also analysed by counting the seconds a movement takes to perform.

BasicMOST® System — General Move — A B G A B P A

Index x 10	A Action Distance	B Body Motion	G Gain Control	P Placement	Index x 10
0	≤ 2 in. (5 cm)			Pickup Toss	0
1	Within Reach		GRASP: Light Object Light Objects Simo	PUT: Lay Aside Loose Fit	1
3	1 – 2 Steps	Sit or Stand Bend and Arise 50% occ.	GET: Light Objects Non-Simo Heavy or Bulky Blind or Obstructed Disengage Interlocked Collect	PLACE: Loose Fit Blind or Obstructed Adjustments Light Pressure Double Placement	3
6	3 – 4 Steps	Bend and Arise		POSITION: Care or Precision Heavy Pressure Blind or Obstructed Intermediate Moves	6
10	5 – 7 Steps	Sit or Stand with Adjustments			10
16	8 – 10 Steps	Stand and Bend Bend and Sit Climb On or Off Through Door			16

Fig. 16 MOST General Move lookup table (Zandin, 2003).

Activity	Sequence Model	Parameter
General Move	A B G A B P A	**A** Action Distance **B** Body Motion **G** Gain Control **P** Placement
Controlled Move	A B G M X I A	**M** Move Controlled **X** Process Time **I** Alignment
Tool Use	A B G A B P A B P A	**F** Fasten **L** Loosen **C** Cut **S** Surface Treat

Fig. 17 MOST sequence models, (Zandin, 2003).

3.4 Spaghetti diagrams

Chapter goal
To clearly communicate assembly movements, a visualisation method is applied. A textual description can be more concise, yet harder to imagine. To quickly and accurately describe assembly movements, spaghetti diagrams are applied (Allaboutlean, 2015). A spaghetti diagram is a visual analysis of the route of a product, a document or the employees. The product can be “followed” when the analyst focusses on the lead time of a product. Or the focus can be on the routing of the staff, to determine whether the workplace is organized ergonomically and efficiently (Bialek, Moran, & Duffy, 2009; The lean six sigma company, 2018). The spaghetti diagram is made by drawing arrows on a top view of the assembly situation to represent the performed movements of the assembler.

These spaghetti diagrams provide a clear overview of the difference between original and improved situation. The improved situation of the assembly line has less arrows and shorter arrows, indicating that there are less movements occurring. This also cleans up the top view of the assembly station as a result. The clarity of the top view changes is useful for the communication of the results. An example of a spaghetti diagram is depicted in figure 18. Although the visualisation of the rooting makes movements more comprehensible in one overview, detailed information is lost if only the spaghetti diagram is provided therefore, the spaghetti diagram is used to support text-based movement descriptions. This is useful to visualize the current state of the assembly line and the adapted situations of the assembly line.

Conclusion
The spaghetti diagrams are used to clarify which movements occur at assembly stations and what the impact of these changes are. It is important to keep the text-based descriptions of the assembly movements to prevent the loss of accuracy which comes with the simplified overview.

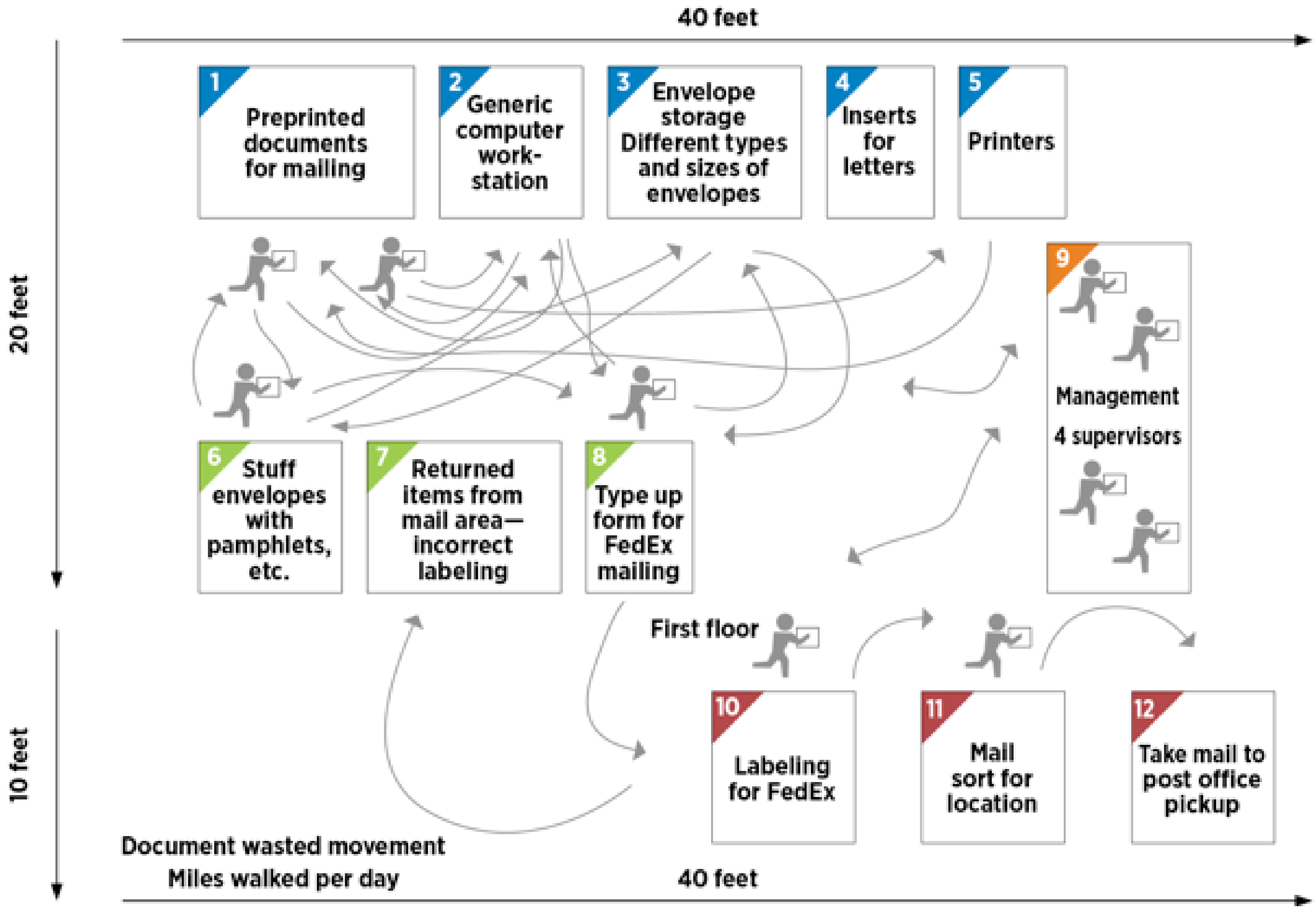

Fig. 18 Example of spaghetti diagram (The lean six sigma company, 2018)..

3.5 Line balancing

Chapter goal
A way to improve assembly lines is to lower the cycle time by redistributing the assembly tasks so that every assembly station works on full capacity without having to wait for a longer taking operation, called the bottleneck operation. To redistribute these tasks, line balancing can be applied. This is visualized in figure 19 and 20.

Line balancing is the process of distributing the workload over assembly stations so that the assembly station "flows" with minimal waiting time.
Tact time is the rate at which you need to complete a product in order to meet customer demand. For example, if you receive a new product order every 4 hours, to meet demand, your team needs to finish a product in 4 hours or less. (Kanbanize, 2020)

Line balancing steps
The steps for line balancing are (The lean six sigma company, 2018):

1. Determine the tact time.
2. Divide the overall assembly time into chunks based on the tact time.
3. Determine which activities at each station add customer value, business value or are waste.[1]
4. Eliminate the waste and business value adding activities.[2]
5. Balance the assembly line according to the tact time by evenly redistributing the workloads.

The first step in line balancing is determining the tact time. The tact time is calculated by:

Tact time = time available / customer demand

in market pull type industries (The lean six sigma company, 2018). A market pull industry is a market where market pull is the relevant factor for production: "Market pull is where the market is need of a product, so designers make a product to meet that need." (DesignMKNG, sd). Since Accell produces bicycles, they deliver a seasonal product which is primarily sold in the spring/summer. Therefore, Accell makes use of a market push type industry. This type of industry operates based on predictions for the sales a year in advance. Therefore, tact time based on customer demand does not apply in this situation. What does apply however, is the assembly line cycle time, which also can be optimized in similar fashion. Once the cycle time is known, the line balancing steps provided above can be implemented to reduce waiting time, reduce bottlenecks, reduce material queueing and reduce assembly time.

Conclusion
Although the application of line balancing is relevant for the improvement of assembly lines, it does not improve the assembly operations itself. The redistribution of assembly tasks through line balancing is therefore out of the project scope. It is, however, interesting to investigate the application possibilities of line balancing after the implementation of assembly line improvements. This can be used to fill the excess of assembly time an assembler receives when assembly operations are optimized.

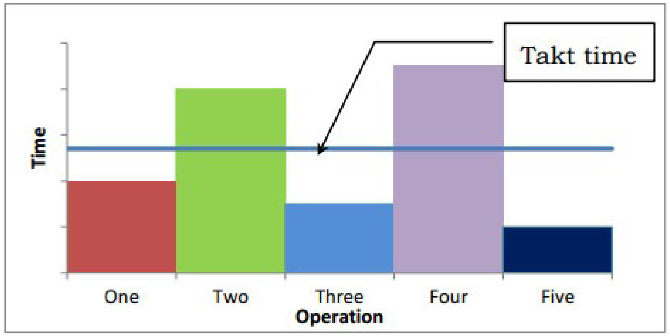

Fig. 19 Unbalanced assembly line (leanmanufacturing, 2014).

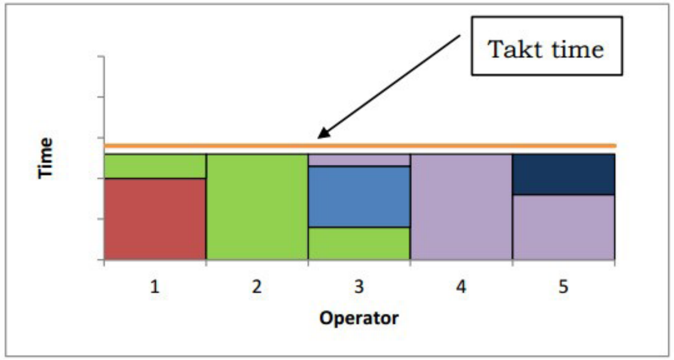

Fig. 20 Balanced assembly line (2014).

1 In this investigation, the similar approach of the Toyota Production System by dividing work into value-added work and non-value-added work is applied due to its simpler applicability over a large set of data.
2 In this investigation, these are categorized as non-value-added work.

3.6 Kaizen root cause analysis, the five whys

Chapter goal
When non-value-added work is found, the Toyota Production System aims to solve the issue by finding and eliminating the root cause behind the non-value-added work. (Taiichi, 1988)

Once that root cause is solved, this specific non-value-added work does not reoccur. The assembly process consists of a large variety of assembly movements. If a method is used to identify the root causes behind the varied non-value-added movements, this movement must be able to process this variety of non-value-added work aspects. If the investigation method is to be used by assemblers at the assembly line, it is important that the investigation method can be directly applied in this practical situation.

In the lean methodology, the kaizen (continuous improvement) root cause analysis method "The five whys" is used for this purpose because of its practicality and versatility. The method is described as follows: "Underneath the "cause" of a problem, the real cause is hidden. In every case, we must dig up the real cause by asking why, why, why, why, why. Otherwise, countermeasures cannot be taken and problems will not be truly solved." (Taiichi, 1988) This means that the root cause behind the non-value-added movements can be found in a variety of situations, and that the root causes can be found using this method.

This method is illustrated with the following example (Spears, 2010):

- The vehicle will not start.
Why?
- The battery is dead. (First why)
Why?
- The alternator is not functioning. (Second why)
Why?
– The alternator belt has broken. (Third why)
Why?
– The alternator belt was well beyond its useful service life and not replaced. (Fourth why)
Why?
– The vehicle was not maintained according to the recommended service schedule. (Fifth why, the root cause).

Conclusion
This approach allows the investigator to transform the found improvement opportunities to the root problems which require solving. After the root cause problems are laid bare, improvements can be proposed to solve the issue. The next chapter details the way in which the improvement opportunities are found based on a list of requirements. If the question "why?" is asked for various non-value-added movements, it could be possible that multiple reasons could be found to explain the occurrence of the non-value-added work. Therefore, this method must be applied with care to ensure that no tunnel-vision towards the same found cause occurs.

3.7 List of requirements

Chapter goal
In this chapter, the goals of Accell are translated into evaluation criteria for assembly line movements. This makes it possible to compare a proposed improved situation to the current situation of Accell on these goals. Translating the goals into evaluation criteria per goal makes it possible to determine the relevancy of the found solutions for the project, by determining their impact on these five goals. Practically speaking, these evaluation criteria can be applied to the specific movements at the assembly stations.

Operations at the assembly line consist of movements. To identify which of these movements are optimal and which can be improved, they are categorized using the Toyota Production System work categorization. Now that it is known which movements are not optimal, it is important to find out why these movements are not optimal, and in which way these movements are not optimal. This is done by comparing the movements to a list of requirements. This list of requirements specifies to which aspects an ideal assembly operation adheres. The list of requirements is based on the literature review and Accell's goals. The requirements are categorized on Accell's five goals for this project. First, the requirements related to the improvement of assembly line efficiency are described.

Requirements for improving efficiency
The Merriam-Webster dictionary defines efficient as "capable of producing desired results without wasting materials, time or energy." (Merriam-Webster, efficient, sd)
In the case of this assembly line investigation, we use the inverse amount of non-value-added work in seconds as the metric for efficiency. If a movement consists of a minimal amount of non-value-added work, it is considered efficient. Since one of Accell's goals is to improve the efficiency of the assembly line, usage of materials, time and energy must be minimized. Minimizing usage of materials means minimizing the amount of materials required to build a bicycle. Therefore, the minimization of used materials can be achieved by for example minimizing dropping material, reducing the production of faulty bicycles and minimizing damaging materials on bicycles.
Minimizing the required time per bicycle means that the bicycles must be assembled in the shortest time frame as possible. This is attempted by making assembly operations as simple and fast as possible, avoiding rework and avoiding unnecessary material (Apple, 1972).
Minimizing the required energy means that the bicycles must be assembled with the least amount of energy required. This is attempted by minimizing the movements per operation, minimizing required effort of the assemblers and minimizing heavy material lifting (Apple, 1972).
The requirements based on these principles are depicted in table 1.

Efficiency list of requirements

Minimize time	*R1.1*	*Parts must not require preparation at the assembly line.*
Minimize energy	*R1.2*	*Parts must not require correction or rework during and after assembly.*
Minimize time & materials	*R1.3*	*Parts must not require unboxing or foil removal.*
Minimize time & energy	*R1.4*	*Parts must not require restructuring or opening.*
Minimize time & energy	*R1.5*	*The assembly movements must be performed without objects obstructing the simplest assembly movement.*
Minimize time & energy	*R1.6*	*Parts must be oriented in one motion to their assembly positions by the assembler.*
Minimize time	*R1.7*	*Assemblers must have all materials available to continue assembly operations without waiting.*
Minimize time	*R1.8*	*The assembly materials must be provided without halting the assembly process.*
Minimize time	*R1.9*	*Breakage of assembly equipment must not cause the assembly line to halt for longer than 5 minutes.*

Table. 1 Requirements for efficiency

Now that the requirements related to improving the assembly line efficiency are described, Accell's second goal will be covered. This page describes the requirements related to the reduction of physical workload of assemblers.

Requirements for improving physical workload

The requirements related to this reduction of physical workload originate from three sources: The EU-OSHA institute which regulates workspaces, the ARBO regulation which is a part of the Dutch law covering workspace environments and the principle of minimizing movements from the Toyota Production System waste determination (Taiichi, 1988). First, the EU-OSHA aspects will be covered.

EU-OSHA states that "At many workplaces, physical hazards are still an everyday occurrence. They are considered a risk factor for work-related musculoskeletal disorders (MSDs) that represent one of the most frequent causes of work-related incapacity to work in Europe. For prevention of work-related MSDs risk assessment of physical workloads is an important part of the risk management process.". (Institute for Occupational Safety and Health of the German Social Accident Insurance, 2020) To protect the assemblers, it is thus important to minimize the physical workloads which cause damage to the individual. EU-OSHA also states multiple risk factors described in the requirements below (Institute for Occupational Safety and Health of the German Social Accident Insurance, 2020). To improve the physical workload for the assemblers, Yoshimura proposes the following improvements: minimizing movement distances, basing movements on natural movements, promoting fluid movements, eliminating unnecessary movements (Yoshimura, 2010). The protection of the assemblers from physical harm is further described in the ARBO regulation (Rijksoverheid, 2020), as depicted in table 2.

The mental and psychosocial workloads associated with musculoskeletal disorders are (Institute for Occupational Safety and Health of the German Social Accident Insurance, 2020): Highly demanding work, poor control/scope for decision making, lack of social support (from superiors/colleagues), insufficient gratification, dissatisfaction with work, workplace insecurity and monotony. This project focusses on the physical aspects of the assembly line. Therefore, although the psychosocial aspects effect the workload of the assemblers, these aspects are outside the scope of the project.

Physical workload list of requirements

Minimize movement	*R2.1*	*Assemblers must not be required to turn to pick up materials.*
Minimize movement	*R2.2*	*Assemblers must not be required to reach for materials.*
Minimize movement	*R2.3*	*Assemblers must not be required to reorient materials.*
EU-OSHA regulation	*R2.4*	*Assemblers must not be required to lift materials.*
EU-OSHA regulation	*R2.5*	*Assemblers must not be required to carry materials.*
EU-OSHA regulation	*R2.6*	*Assemblers must not be required to push materials.*
EU-OSHA regulation	*R2.7*	*Assemblers must not be required to pull materials.*
EU-OSHA regulation	*R2.8*	*Assemblers must not be required to sit without effective breaks.*
EU-OSHA regulation	*R2.9*	*Assemblers must not be required to sit with lack of movement.*
EU-OSHA regulation	*R2.10*	*Assemblers must not be required to stand without effective relief.*
EU-OSHA regulation	*R2.11*	*Assemblers must not be required to work in awkward static/dynamic trunk postures.*
EU-OSHA regulation	*R2.12*	*Assemblers must not be required to perform squatting.*
EU-OSHA regulation	*R2.13*	*Assemblers must not be required to kneel.*
EU-OSHA regulation	*R2.14*	*Assemblers must not be required to lie down.*
EU-OSHA regulation	*R2.15*	*Assemblers must not be required to perform repetitive tasks with high handling frequencies.*
EU-OSHA regulation	*R2.16*	*Assemblers must not be required to perform work involving high exertion.*
EU-OSHA regulation	*R2.17*	*Assemblers must not be required to perform work involving exposure to force.*
EU-OSHA regulation	*R2.18*	*Assemblers must be able to perform operations without prior experience.*
EU-OSHA regulation	*R2.20*	*The assembly operations must be quieter than 80 dB.*
ARBO regulation	*R2.21*	*Assembly operations must adhere to Arbeidsomstandigheden-law. (Arbeidsomstandighedenwet, 2020)*
ARBO regulation	*R2.22*	*The workstations must be designed in a way which avoids occupational health hazards.*
ARBO regulation	*R2.23*	*The degree of physical strain to which workers are exposed should be minimized.*
ARBO regulation	*R2.24*	*The physical factors present at the workplace must not be dangerous to the assemblers.*
ARBO regulation	*R2.25*	*The tools used in work must not be dangerous to the assemblers.*
ARBO regulation	*R2.26*	*Personal protective equipment must be provided if necessary.*
Minimize movement	*R2.27*	*Assemblers must not be required to perform steps.*

Table. 2 Requirements for physical workload

Cost reduction list of requirements
The next goal of Accell for the assembly line is the reduction of assembly costs. Since the assembly costs are linked to the efficiency of the assembly line, only the requirements unrelated to efficient assembly of the bicycle are provided. Here, requirements related to the minimisation of costs and used hardware are described.

Requirements for cost reduction
The Merriam-Webster dictionary defines costs as: *the outlay or expenditure* (as of effort or sacrifice) made to achieve an object (Merriam-Webster, sd). This expenditure at Accell consists of material costs, assembly line worker time costs, energy costs and equipment costs. Therefore, the expenditure is minimized by optimally using materials, minimizing assembly time per bicycle, minimizing assembly operation energy requirements and equipment costs. The requirements based on these sources is depicted in table 3.

Bicycle quality improvement list of requirements
Another goal of Accell for this project is the improvement of the bicycle quality at the assembly line. During bicycle assembly, the bicycle quality is influenced by correct fastening practices and avoidance of damage. Correct fastening practices are already covered in the efficiency requirements. What remains in this category is the minimization of damage.

Requirements for bicycle quality improvement
The Merriam-Webster dictionary defines quality as: *degree of excellence* (Merriam-Webster, sd). To improve the bicycle's degree of excellence at the assembly line, we try to ensure that materials are being correctly assembled and materials remain unscratched. This type of damage is selected as requirement since it was observed at the assembly line and during conversation with Accell's repairmen it became clear that scratching was the most occurring form of damage. The improve bicycle quality requirements are depicted in table 4.

Faulty bicycle reduction list of requirements
The final goal of Accell for this project is the reduction of the number of faulty bicycles, as described in chapter 1.3. Although reducing faulty bicycles is akin to improving the quality of the bicycles, these differ in outcome. Faulty bicycles are detected and repaired before partial reuse of the materials after which they are sold. To reduce faults and defects, we try to minimize the possibilities of damaging the bicycle during assembly. The requirements related to minimizing the possibilities of damaging the bicycles are already covered in the bicycle quality requirements list. Therefore, no additional requirements are presented in this section. This concludes the list of requirements chapter.

Conclusion
The requirements found from the theoretical investigation and assembly situation analysis were used to translate Accell's goals into evaluation criteria. These lists of requirements will be used to investigate the feasibility of the proposed assembly line improvements. This list of requirements is then used beyond the scope of determining if the proposed improvements do improve the assembly line. The outcomes of the proposed method are investigated using the list of requirements as a benchmark for the effectiveness of the method itself. This higher-level use of the list of requirements makes it possible to determine how well the proposed improvement method improves the assembly line towards Accell's goals.

Assembly costs list of requirements

Minimize material & equipment costs	*R3.1*	*Assembly line operations of different bicycles must be possible with the same hardware.*
Minimize material & equipment costs	*R3.2*	*Assembly operations of similar item types must be possible with the same equipment.*
Minimize equipment costs	*R3.3*	*Assembly line situation must not prohibit optimal assembly operations for other bicycle models.*
Minimize equipment costs	*R3.4*	*The implementation costs of an improvement must have positive return of investment after a half year period.*

Table. 3 Requirements for assembly costs

Bicycle quality list of requirements

Minimize scratching	*R4.1*	*Parts must be fastened without the assembler scratching components or the frame.*

Table. 4 Requirements for bicycle quality

3.8 Theoretical background conclusion

This chapter provided multiple methods to investigate the assembly line.

The improvement philosophy of Ford and Toyota is taken as starting point for the ideation of methods for assembly line improvement. The Toyota Production System work categorization method is used as starting point for the analysis part of all prototypes. Based on this classification idea, the first and second prototype expand on it to determine which kinds of inefficiency are observed. It can also serve to estimate the current efficiency of the assembly line. The spaghetti diagrams can be used to communicate the current state and improved state of assembly stations. When applying this method, the image must be accompanied by textual definitions of the movements, to avoid loss of detail. Line balancing is considered outside of the scope of the project since the goal is to improve the assembly line operations. However, it could be relevant for assembly line improvements after the assembly line improvements are applied. The five whys method can be used to find the root causes of non-value-adding movements. The list of requirements allows for methodical comparison of proposed improvements to the current assembly line situation to ensure that assembly line improvements do not violate other requirements. Some of these methods are applied in the initial assembly line improvement method prototypes from chapter 4. Except line balancing, they are all present in the final assembly line investigation method, detailed in chapter 5.

4. Ideation

Introduction Situation Theory Ideation Concept Testing Results Conclusion Discussion

1 2 3 4 5 6 7 8 9

This chapter details the ideation process of creating a methodical approach for the structural improvement of the assembly line. Here, four iterations of such a methodical approach are described. Multiple tests were conducted to determine if the methods improved meaningful aspects of the assembly line, and whether the method was appropriate for the improvement of these aspects. Based these tests, new required features were found for the next iteration. This allowed the methods to continuously adapt to the changed priorities of the method based on the findings from the application of the previous methods. Each iteration therefore builds on the previous version, and the reasons for the next iteration of the methodical approach are described per prototype to justify these choices made. Based on these prototypes, the final version of the methodical approach was constructed. The final version is described in chapter 5. The first step of the prototyping phase was to create an analysis method to understand what kind of movements occurred at the assembly line. This is described on the next page.

4.1 Prototype 1: Video analysis tool for movement categorization

Goal of first method prototype

The assembly line improvement philosophy of Ford (Ford & Crowther, 1923) and Toyota (Taiichi, 1988) state that the assembly line can be improved through the reduction of inefficiencies. This is done by reducing the non-value-adding activities from the work that must be performed. The first goal of the first method was to determine the efficiency of the assembly operations from the video footage. This was done by categorizing every second of the assembly footage into seven categories of assembler movements. These categories and their occurrence at the assembly line is displayed in figure 21:

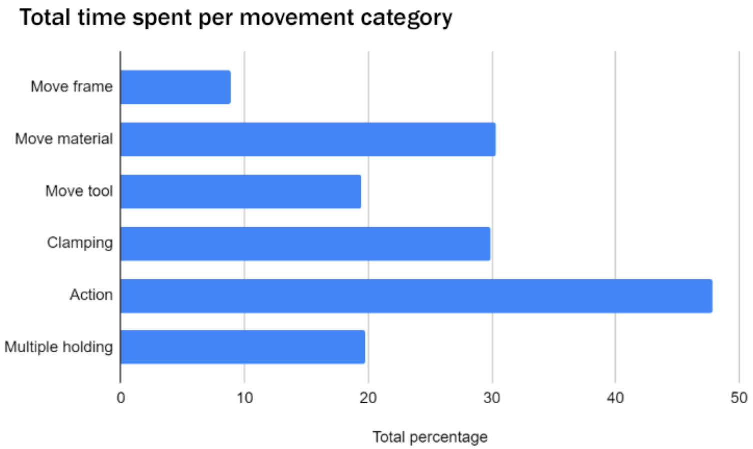

Fig. 21 Total time spent per movement category.

The category "Action" is considered a value-adding activity. The other six categories are considered non-value-adding activities. During assembly operations, multiple movements occur simultaneously. Therefore, multiple movement types could occur simultaneously. The result of this categorization was that the efficiency of the assembly line is 47%. Here, it can also be seen that there is opportunity to improve the assembly line efficiency by reducing the non-value-adding movements of which 53% of the footage consists. Focussing on the minimization of moving material or clamping could potentially lead to the largest time reduction, since both occur during 30% of the video footage.

To further maximize the impact of proposed changes to assembly line operations, the focus is aimed at often occurring assembly operations. This would allow the application of improvements to similar operations at other stations as well. Therefore, the second goal of the first iteration of the method was to categorize the types of operations and registering their occurrence. The video footage of the 16 assembly stations was categorized per second of video footage into one of eight categories. These categories were based on the observed assembly operation footage itself. The categories and their occurrence are depicted in the confidential figure below.

The figure is not depicted here due to it containing sensitive information. Therefore, it is excluded from the public report. In the confidential report, a overview of the assembly operations and how much seconds are spent per assembly operation is depicted.

From this overview, we find that 34% and 31% of all operations consist of fastening by screwing and fastening by placing. Therefore, improvements to these operations have higher potential to be reused for other assembly stations and should be focussed on.

Applying automation solutions for fastening by screwing and fastening by placing looks promising based on these findings due to their common occurrence. However, at this stage, it is unknown whether these operations are suitable for automation solutions. Therefore, the goal of the second iteration of the method must include a way to determine how suitable the movement is for automation solutions. Furthermore, at this point the method only provides insight on the current state of the assembly line, no improvements are proposed based on this information. A future version of the method must go beyond the analysis steps and allow the investigator to ideate solutions for the found inefficiencies at the assembly line.

Conclusion

From the application of the first method prototype, we find that the overall assembly line efficiency is 47% and that the most occurring assembly operations are fastening by screwing and fastening by placing. To know whether automation solutions can be applied for these operations, the method must be expanded to estimate the automation potential of the assembly operation. This addition to the method is described in the next chapter. The method must also become able to support the investigator in the ideation of solutions for the found inefficiencies. This is added at a future prototype.

4.2 Prototype 2: Video analysis tool for automation possibilities

Setup of video analysis tool for automation possibilities

The first method provided insight in which operation types could best be improved to reduce time and energy spent at the assembly line. However, it did not provide insight on the automation potential of investigated movements. This functionality is added to the method in this iteration. The automation potential of assembly movements is estimated by scoring these movements on three aspects relevant to automation:

- The required degrees of freedom of the movement being performed.
- The complexity of the material being manipulated.
- The number of actuators required to complete the assembly operation.

The required amount of degrees of freedom which an operation requires the assembler to perform is used to score the automation potential. Every rigid body has six degrees of freedom: three for translation and three for rotation (Thomas, 2020).

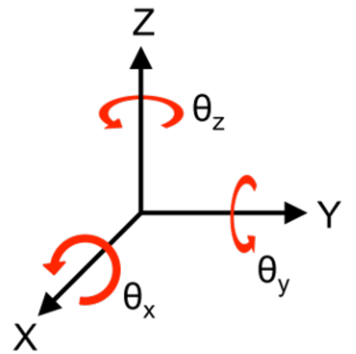

Fig. 22 Degrees of freedom, (Thomas, 2020).

This means moving the object along one, two or three axis or rotating the object around one, two or three of these axis. For example, a screwdriver moves along 1 axis (Y) and rotates around that same axis during fastening (θY), as can be seen in figure 22. An example of a movement with 6 required degrees of freedom is guiding the bicycle's cables through the bicycle frame. This requires movements in the X,Y and Z directions while being rotated along these axis as well, see figure 23. Since this movement is more complex than the example of the screwdriver, an automation solution for this movement must also be capable of movements in more degrees of freedom. If an assembly automation needs to be more forgiving, it will become more expensive (Nof, 1997, p.84). This makes movements with more degrees of freedom more expensive to automate. Since the investment costs rise with increasing complexity of the assembly movements, the use of human assemblers is preferred for complex movements to minimize costs. These 6 degrees of freedom are used to score the automation potential. Therefore, a lower required amount of degrees of freedom generally has a higher potential for automation.

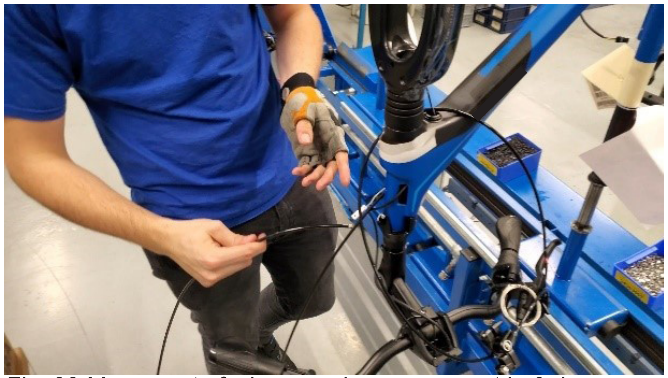
Fig. 23 Movement of wires requires movement in 6 degrees.

The material of the material is included since it also influences how complicated an automation solution must be. Manipulating materials which are flexible are generally harder to process using automation solutions since the material can change position during the movement (Nof, S. Y., Wilhelm, W. E., & Warnecke Hans-Jürgen, 1997). Materials with a complex shape also have a lower potential for automation since the gripper of the automation solution needs to be more complicated. A scale based on these two starting points is presented in figure 24. Doltsinis(2013) describes that selecting the right metrics for decision making requires simplified metrics to support decision making. The parameters were therefore chosen based on their clarity and simplicity.

Fig. 24 Material complexity.

The number of actuators required to complete the assembly operation is based on the amount of hands the assembler must use for an assembly operation. For some operations, using one hand is enough. Other assembly operations require both hands to be used, such as holding a material in place during fastening.

These three aspects were used in the following formula to score the automation potential per movement:

*(Degrees of freedom + Material complexity) * Number of actuators = Automation difficulty index*

Although this formula does not perfectly determine the difficulty in all cases, it provides a workable method within the time available for this project. For further research, this could be further explored by removing the index and weighing the factors differently.

Results video analysis tool

The assembly line footage of all 16 stations was analysed using this method. For every second of video footage, the automation potential based on these three metrics was estimated. The whole list of assembly operations and their respective scorings can be viewed in appendix C. The investigation of the automation potential found that two types of assembly operations were best suited for automation solutions:

1. *Fastening using bolts and screws.*

This type of operation scored an automation difficulty index of 3. Fastening using screwing requires two degrees of freedom (forward in one direction and rotation along that direction) and score a 1 on the material complexity level. This is due to the material having a standardized gripping location. Only one actuator is required to fasten bolts and screws. Therefore, the automation difficulty index of (2 + 1) * 1 = 3 is assigned.

2. *Fastening simple materials by placing using linear movement*.

The other low scoring operation is fastening by placing using linear movement. This type of operation scored a 2, since only one degree of freedom is required (forward) and the materials are simple, scoring a 1 on the material complexity level. Since only one actuator is required for these types of operations, the automation difficulty index of (1 + 1) * 1 = 2 is assigned.

Since these assembly operations score lowest on automation difficulty, these tasks are more likely to be easier to automate. From the first iteration of the method, it was discovered that fastening using screwing and linear placement occur most often. Since these operations also score lowest on automation difficulty, it is wise to focus on these tasks which are performed most while being the least complex.

Sub-assembly investigation

As can be viewed in appendix C, most other assembly operations are more complicated to automate due to them requiring more complicated movements or use more complicated materials such as placing cables which requires many degrees of freedom and uses flexible material. Other movements are complicated due to the simplest movement being blocked by other parts or the bicycle frame itself. It is suspected that this blockage of assembly locations is caused by the current order of assembly, since materials are found to block the assembly of other bicycle parts. Another cause could be that the blockage originates due to the bicycle orientation being up-side down during assembly. A third cause could be that the fastening locations are chosen in the current design in a way that assembly is not as simple as it could be. To determine which of these aspects are the cause of the complicated assembly operations, a practical investigation is performed. In this investigation, the influence of the order of assembly operations and the possible orientations on the required degrees of freedom was investigated. This investigation and its results can be viewed in appendix D.

Sub-assembly investigation results

The result of the investigation were that the design of the bicycle complicated assembly operations due to blockage of movement, limited access to assembly locations and that the bicycle was designed so that the order in which the assembly operations has to be performed caused blockage of other assembly operations. Solutions for these problems included changing the bicycle design based on design for assembly practices and the implementation of sub-assemblies where the assembler has more movement space available for the assembly operations. However, changing the bicycle design is not possible for the current version of the bicycles and therefore out of scope for this project. Sub-assembly usage is also out of scope due to it found limited applicability (Three possible sub-assemblies were found: The bicycle frame, the front fork and the luggage carrier, appendix D). Although the implementation of sub-assemblies provides easier access to assembly parts and potentially reduces assembly time, the logistics of moving material to additional assembly locations and increasing the amount of re-handling of the materials after assembling are downsides to this approach. Since other assembly operations could not be improved using the sub-assembly strategy, it was abandoned in this investigation for finding a method which can be incrementally applied.

Findings from second method application

The sub-assembly investigation resulted in the finding that the bicycle design limited the possibilities of automation solutions. Together with the found hurdles for automation in the context analysis, the improvement of the assembly line through automation is no longer pursued. Instead, improving the assembly lines using optimization is pursued. Due to this shift in focus, the next iteration of the method must include ways to repetitively optimize the assembly line. Optimization of the assembly line requires cooperation between the various stakeholders of the assembly process. This is due to the knowledge of the various aspects of the assembly line being distributed among the various stakeholders, as described in image 94. To optimize the assembly line situations, the method must go beyond numerical analysis of the assembly operation. After analysis, it must provide ways for these stakeholders to define the problems at the assembly line, ideate solutions for these problems and provide ways to test these ideated solutions. To make the method applicable by the various stakeholders, it is attempted to tailor the method to the various stakeholders in the next chapter. From the context analysis it was found that the origins of the non-value-adding movements are not only physical environment or bicycle design related. Other found sources of inefficiency are lack of communication, lack of power tool usage and lack of line balancing. Since these are also possible causes of inefficiency, the next method which aims to optimize the assembly line must be able to find solutions for these problem sources as well. The inclusion of these aspects is detailed in the next chapter.

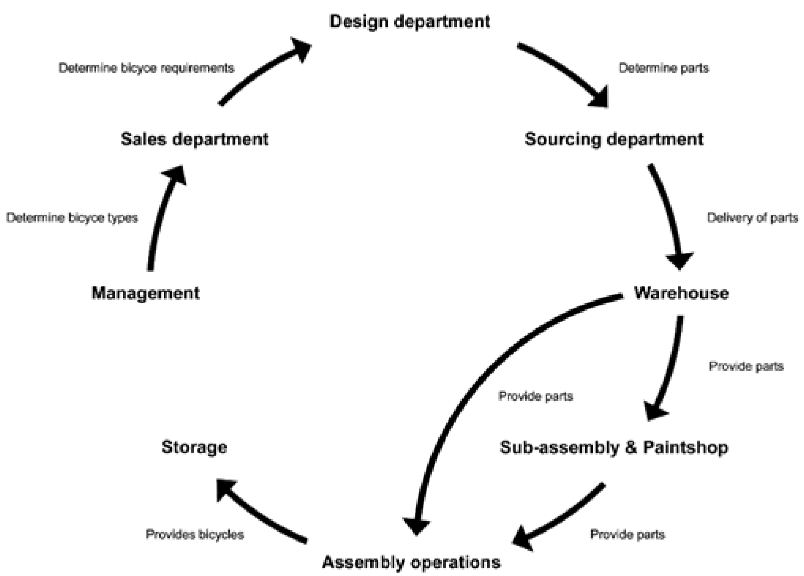

Fig. 25 Production cycle of a bicycle at Accell.

Setup of initial framework
To make a method which can turn assembly line footage into applied improvements, the steps required to achieve this transition must be determined As can be seen in figure 26, the first half of the steps zoom in on the most important problem at the assembly line by asking why the investigated assembly movement is inefficient and which properties of the movements make the assembly operation ineffective. When the origin of the inefficiency is found, ideation can start. These ideas can then be verified and applied. Since the improvement framework should be usable for various stakeholders, it was reasoned that the framework should be customizable by the stakeholder to use investigation methods which were most relevant to the situation of the investigator. For example, an assembly line worker does not have time to analyse video footage but is able to brainstorm solutions during the morning meeting. Based on this viewpoint, at every step of the framework, various design methods from the Delft Design Guide(Zijlstra et al., 2013) could be applied. For the ideation of this method, various cards of relevant investigation methods were made, see figure 27. The full overview is depicted in appendix E.

The idea was that the various stakeholders could support assembly line improvement by contributing to aspects which were relevant to them. For example, including the management in the process to enable purchases of new equipment or including the design department in the ideation phase to simplify assembly operations through bicycle redesign.

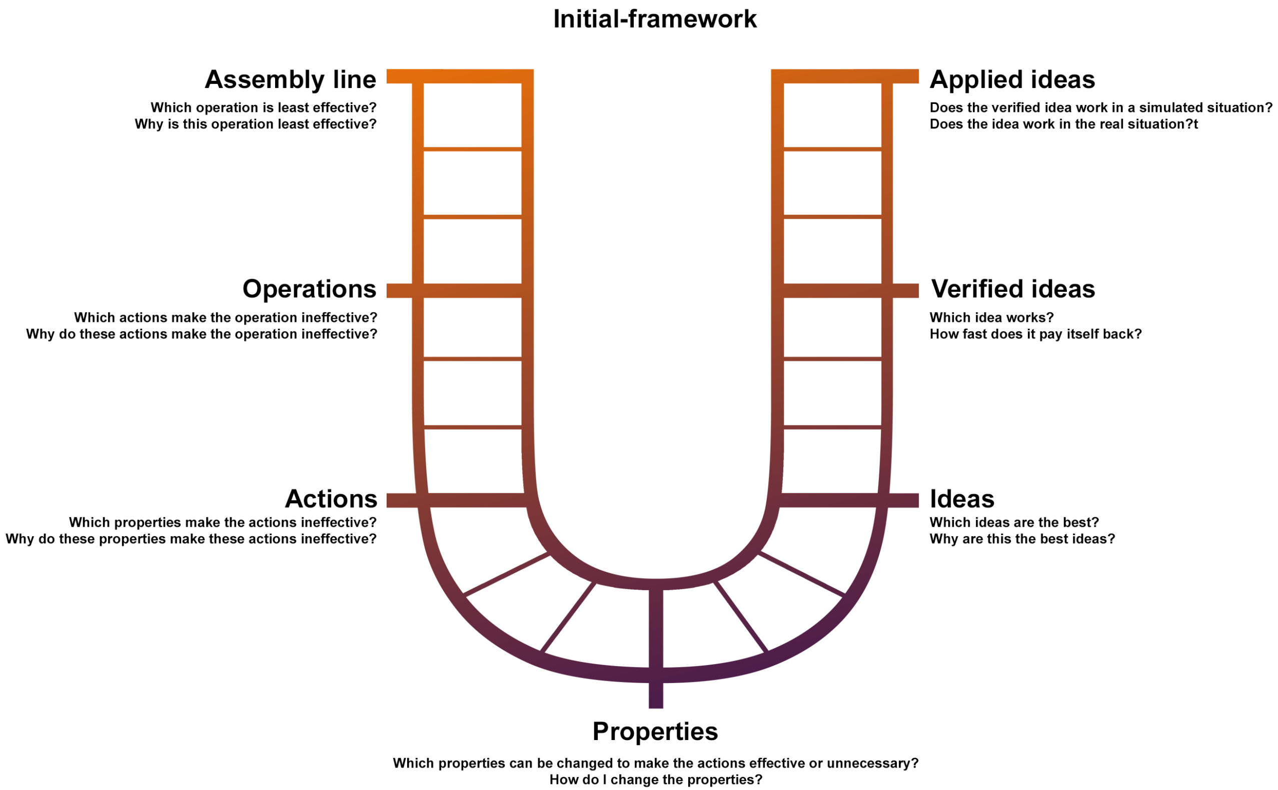

Fig. 26 The prototype of the initial framework.

Testing the initial framework
To determine if the application of the initial framework reduces assembly inefficiency, two tests are performed. During these tests, the initial framework is tested in three steps:

1. Determine if the initial framework indicates the two largest time-wasting operations on the assembly line.
2. Determine if the ideation methods provide solutions which eliminate or reduce the non-value-adding operations.
3. Determine if the found solutions are economically viable.

Since a variety of design methods can be applied per investigation step of the framework, a selection was made for these tests. The overview and explanation of these specific methods, appendix E, can be visited. For the investigation of the assembly line footage, the method data centric design was used to find the most non-value-adding operations. To ideate an improvement, the Wwwwh and How-tos ideation method were applied. The Wwwwh method is a method which asks the investigator questions to create understanding of a situation. It is displayed in image 96. The How-to's method is defining a problem by asking yourself "How to solve X" multiple times. These methods are aimed to determine what causes the current situation to be like it currently is and how the assembly situation can be improved. The use of the methods is described in appendix E. For the comparison of ideated outcomes, a Harris profile was used. To determine if applying the improvements to the assembly situation is economically feasible, the cost price is estimated.

Fig. 27 Assembly cards used for the initial framework.

Test 1

The first test consisted of applying the initial framework to the assembly line video footage and sequentially applying the methods described above. First, the assembly operation which contains most non-value-added time was found using the data centric method. In this case, the operation “Moving the frame” at station 6 was found (Figure 29). In this operation, the assembler waits for the assembly line to move, lifts the bicycle frame from the manual assembly line, walks to the automated assembly line and places the frame on the automated assembly line. The video footage of this operation can be retrieved from the data package on the NextCloud of the RoboFiets project. Using the ideation method mind mapping, the solution of connecting the two assembly lines with a rail piece and moving the control box in-between would save 24 seconds per produced bicycle. The next step is to determine the economic impact of this improvement, which is included in the confidential appendix F. The return of investment (returns/ investment) is estimated to be 397% over a five-year period. Since the other assembly lines also have this division between the manual and automated assembly line, this proposed improvement is scalable

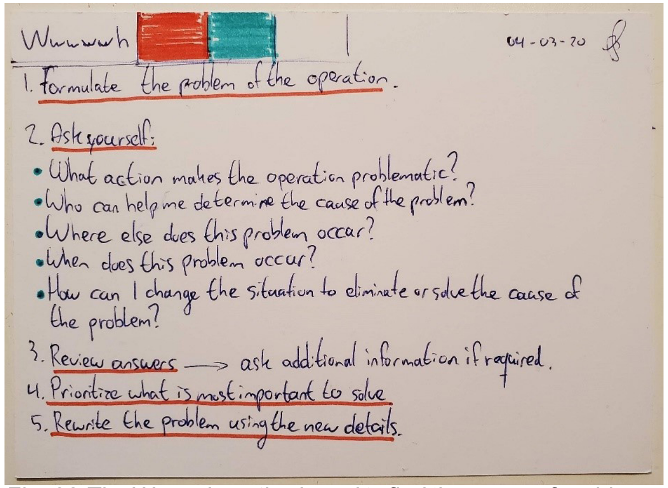

Fig. 28 The Wwwwh method used to find the cause of problems.

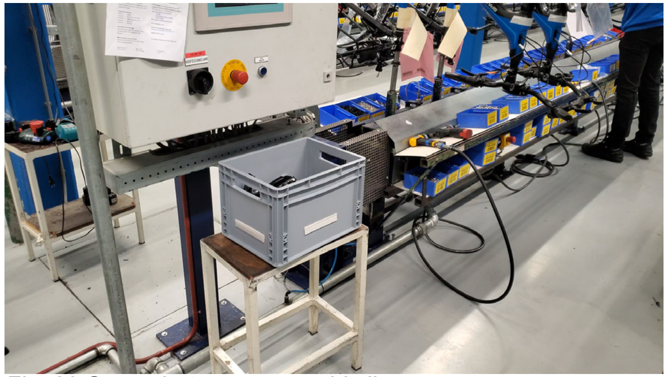

Fig. 29 Space between assembly lines.

to the other assembly lines as well.

Test 2

The second test of the first framework consisted of reapplying the initial framework to the assembly line video footage and selecting the second most non-value-adding operation using the method sequence described in test 1. By applying these methods, the operation of tightening the bolts and nuts at station 8 consists of 19 seconds of non-value-adding time. In this operation, the assembler fastens two bolts and three nuts using a pneumatic nutrunner. Then, he fastens the nuts and bolts to the correct torque using two torque wrenches. The video footage of this operation can be retrieved from the data package on the NextCloud of the RoboFiets project. By applying the Wwwwh method (figure 28), it was found that the use of the two torque wrenches in this scenario would not be required if the nutrunner would fasten to the correct torque and provide feedback that this would be possible. After further investigation into assembly tools, the Atlas Copco ETP TBP 61-32-10 automatic screwdriver was selected as solution example (Figure 30). This screwdriver can fasten the nuts and bolts to the correct torque, eliminating 16 seconds of assembly time per assembled bicycle. The economic impact of this solution proposal can

Fig. 30 Proposed screwdriver with torque control .

be found in the confidential appendix F. The return of investment (returns/ investment) is estimated to be 313% over a five-year period. Since this assembly operation occurs at multiple assembly lines, it is scalable to other assembly lines as well.

Findings from the first framework

From the investigation of the first framework, it was found that the application of the methods data centric design, Wwwwh and how-tos successfully found the most non-value-adding time containing assembly operation and that the sequence also was able to support ideation for improvement possibilities. The economic impact of these improvements seem valid as well. During the investigation, it became clear that the act of determining what the problem at the at the assembly station was already gave rise to multiple solution ideas. Therefore, it seems possible that the amount of possible investigation methods can be

reduced. This can create a framework that has clearer aim and can be applied without having to find out which method you want to apply. The next iteration of the framework must therefore have less methods and provide the investigator with methods which are proven to work in this framework.
If multiple stakeholders are to participate in the improvement of the assembly line, it is necessary that they are motivated to spend time on the improvement of the assembly line. Therefore, the next iteration of the assembly line must include a way to motivate the various stakeholders in cooperating towards the improvement of the assembly line. In this cooperation, the stakeholders can contribute their knowledge from their area of expertise. Sharing this expertise to come to a solution must therefore also be included in the framework.

Conclusion from the first framework

The tested sequence of data driven design and then applying Wwwwh was able to find the most non-value-adding time containing operation. The ideation method was not necessary for the two tests, since the solutions became apparent when the cause of the inefficiency was found. To solidify the framework and to base it on methods that seem to work, the next iteration must consist of a set sequence of methods. Since multiple stakeholders must participate in the assembly line improvement, they must be motivated to help. This requires a source of motivation, which must be included in the framework.

4.4 Prototype 4: Robofiets-framework

Setup of RoboFiets-framework
From the initial-framework testing, a feasible assembly line optimization method arose. To make the method easier to use, the variety of methods from the initial method was reduced. Another outcome of the initial framework was that collaboration could be used to get to the next step in the investigation. Therefore, the use of expert knowledge and collaboration are assigned at the steps between action and applied ideas, see figure 31. In this framework, the analysis can start in two ways. Either the investigator himself/herself performs video analysis using data centric design to find the action which must be improved, or an expert proposes an assembly problem he/she encounters during work. To make the framework easier to apply, the video-analysis method is reduced to deciding whether a second of assembly footage consists of value-added work or non-value-added work (Taiichi, 1988), as described in chapter 3.2.

Motivating stakeholders to participate in assembly line improvement
To motivate the stakeholders to participate in the improvement of the assembly line, the step incentive is added at the end of the RoboFiets-framework. In this step, the stakeholders should receive reward based on the outcome of the investigation. Managers of large corporations often claim that it is hard to motivate their employees to be more creative. (Landier, 2002). To overcome these difficulties, business consultants have argued that nurturing corporate culture that allows freedom to experiment and tolerates failures is essential to motivate innovation among employees of large corporations. (Manso, 2011). To motivate the stakeholders to perform improvements to the assembly line, an incentive structure is required. Optimal innovation-motivating incentive schemes exhibits substantial tolerance (or even reward) for early failure and reward for long-term success (Manso, 2011). Therefore, the participant should be rewarded if the improvement is successful and protected from criticism or reprimands if the improvement is unsuccessful (or even rewarded for the initial improvement attempt). For this step of the RoboFiets-framework, the following reward is proposed: Provide the person responsible for the reduction in assembly costs 10% of the resulting cost reduction per affected bicycle for a determined amount of time. Since this bonus is paid from the cost reduction, this incentive does not add costs to the company up front.

Results from RoboFiets-framework
In discussion with the coaching team, it was decided that the incentivation of stakeholders and pursuit of collaboration between stakeholders was not a valid outcome of a graduation project for the master Integrated Product Design, since the result is strategic in nature and does not provide a tangible outcome. Therefore, the motivation of stakeholders

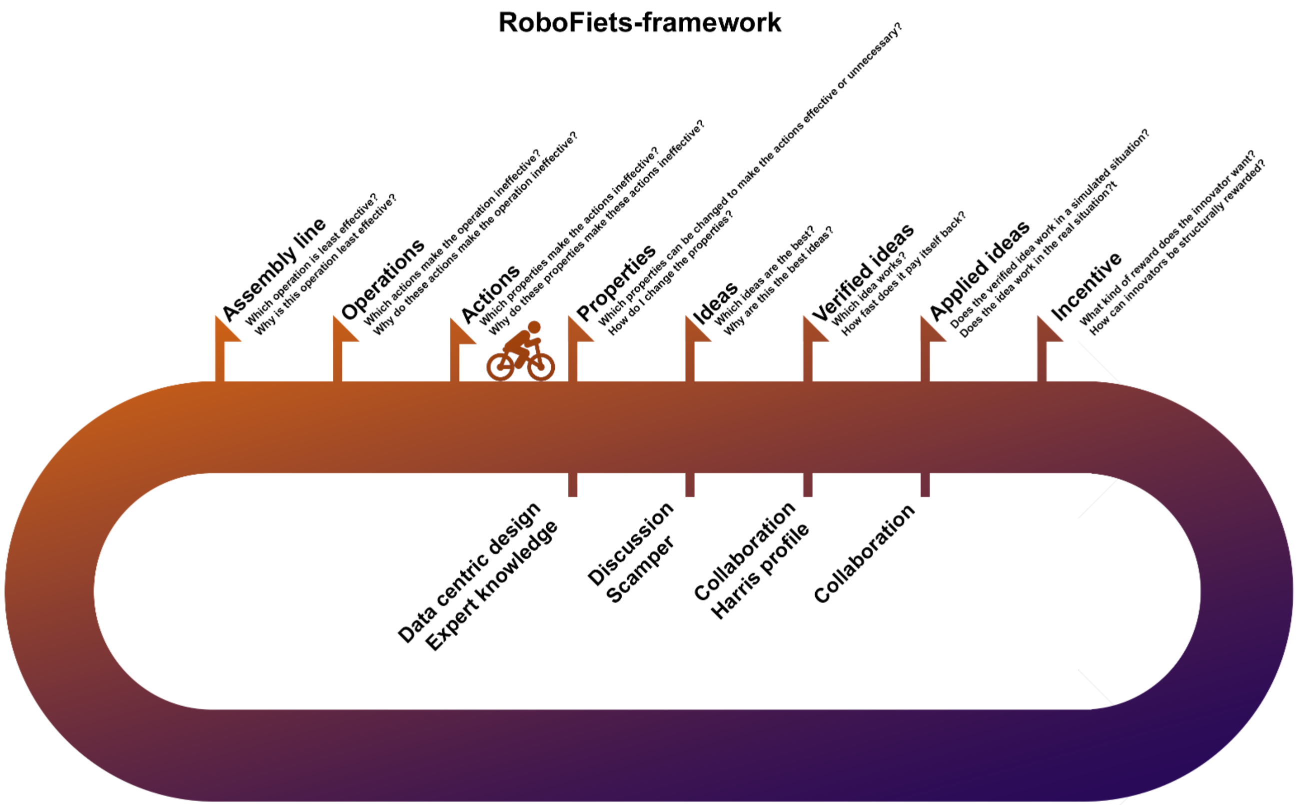

Fig. 31 Visualisation of the RoboFiets framework.

was no longer pursued. Due to the covid-19 situation, testing the framework in the assembly hall became infeasible. Therefore, it was decided that the outcome of the project must be a method which can be applied to video footage by future researchers of the RoboFiets project. Therefore, the method must be realigned to support investigation by future researchers instead of the personnel of Accell. This makes more in-depth investigation possible due to the focus of the researchers being fully on assembly line improvement, instead of the stakeholders which simultaneously must perform other work. This allows the methodology to be more in depth.

Conclusions of prototyping chapter

The investigation on the initial video analysis tool found that the efficiency of the assembly line was 47%. The occurrence of assembly movements was investigated, and most time at the assembly line was spent on screwing and fastening. During the investigation of the automation potential analysis tool, it became clear that fastening using screwing and fastening using placing are most suitable for automation solutions. However, during the sub-assembly investigation it was found that redesign of the bicycles would be preferable before applying automation. At the current state of the bicycle, assembly movements are blocked due to the geometry and assembly order of the parts. These assembly issues must be resolved before feasible automation can be applied. The tests from the initial framework found that the methods sequence of video analysis, Wwwwh and How-tos resulted in the improvement of assembly line situation which reduced the assembly time by 24 seconds at station 6 and 16 seconds at station 8. This indicated the viability of using a sequence of methods to enable the structural investigation and improvement of the assembly line. This was further investigated in the RoboFiets-framework, where a incentive structure was added to the sequence. Due to the covid-19 situation, the focus was shifted from making the method applicable by various stakeholders to making the method applicable by future researchers. This leads to the possibility of making the improvement method sequence more in depth. It also led to the discontinuation of the incentive structure. The next chapter details the final version of the assembly line improvement method. This method builds upon the original analysis method and is strengthened by literature. For the ideation steps of the investigation, the knowledge gained from the initial framework that understanding of the cause of the problems naturally led to finding solutions is also implemented. The method is described step by step in chapter 5.

5. Concept: proposed assembly line improvement method

Introduction 1 — Situation 2 — Theory 3 — Ideation 4 — **Concept 5** — Testing 6 — Results 7 — Conclusion 8 — Discussion 9

This chapter details the final method, applied to come from video footage to practical testing. This method is based on the iteration of the RoboFiets framework as described in the previous chapter. The method itself is one of the three final deliverables, which Accell can use to structurally investigate and improve their assembly lines. To test the validity of the method, it is applied on the ABC Model assembly line. This investigation focusses on the 5 largest improvement opportunities of the assembly line. For these improvement opportunities, a multitude of improvements is proposed. Three of these improvements are tested in a rebuild assembly line environment to verify the validity of the proposed assembly line improvement method.

Since the outcome of the project needs to be viable for the long term, the solution must be repeatable. Therefore, it is important to find a solution which can be implemented multiple times. To provide a repeatable approach, a structure of video analysis is provided, based on the previous iterations and the supportive literature. This guides the investigator in his process of finding the important assembly problems and finding the problems with the individual movements. Up until that point, the investigator is not yet using his own creative skills and knowledge on the subject. Since these aspects of the investigator can be leveraged (The lean six sigma company, 2018), the method provides room for creative freedom. This is done by using the five whys and the common sense approach, which is further described in chapter 4.8 and 4.10. The creativity of the user is guided to gain more consistent results by categorizing the root cause problems, so the investigator knows where to look for solutions.

5.1 Overview of method

The current situation of Accell is described and the ideal situation is also defined using the list of requirements which is based on Accell's goals, the Toyota Production System (Taiichi, 1988) ideology, OSHA (Institute for Occupational Safety and Health of the German Social Accident Insurance, 2020) and ARBO (Rijksoverheid, 2020). To move from the current situation towards the ideal situation, a combination of methods is used. This approach serves as a deliverable for this project, which Accell can use to repetitively improve their assembly lines.

The sequence of methods presented here aims to transform video footage from an assembly line into practical improvements. This is done by first determining which assembly line movements must be improved. Then, the root causes of these movements are investigated. Once these root causes are known, solutions for these root causes are proposed and tested. The sequence presented below is aimed to reach those goals in that sequence to come to substantiated solutions. The method presented here are the result of investigation of the literature on assembly line improvement and lean practices. For every individual method in the following chapters, the sources are included.

Method sequence

The following sequence of methods is used:

Step 1: Find the least efficient operations. Video analysis using the Toyota Production System work division into value-adding and non-value-adding work.

Step 2: Define actions by specific movements. Use the MOST system to structurally name the specific movements per action.

Step 3: Determine which movements are ineffective. Use the MOST system to structurally estimate the time spent per action. Since the MOST system was found to be inaccurate in the case of the ABC Model assembly line, regular second by second determination of work into actions and value-adding and non-value-adding work were used.

Step 4: Compare the current situation to the ideal situation using the list of requirements.

Step 5: Find the root cause of the problems. This is done by using the Toyota Production system Five Whys.

Step 6: Categorize root cause problems. This is done either by the level on which the root problem occurs, or on the category of problem type.

Step 7: Propose solutions per root cause problem. Use the common sense approach to solve the root cause which is already determined and categorized for the investigator.

These steps are visualized in figure 32, which will serve as a guide for this chapter.

For step 1 and 3, the Toyota Production System was applied to determine which assembly movements to improve, as described in chapter 3.2. For step 2 and 3, the MOST system analysis method was applied to define the specific movements and estimate the time required per movement. This was covered in chapter 3.3. The list of requirements used in step 4, to quantify the ideal situation, was covered in chapter 3.7. The root cause analysis of step 5 was covered in chapter 3.6. The categorization in step 6 originated from the outcomes of the investigation itself. This will be covered in chapter 4.10. The propositions of root causes in step 7 use the common sense approach, which is detailed in chapter 4.11.

The sequence of methods is the deliverable which can be repetitively used by the investigator to structurally improve the assembly lines. After the assembly line improvements are performed, the investigator can investigate the current state of the assembly line balance and adjust to lower the cycle time by relieving bottleneck situations from their list of tasks. The application of the method sequence proposed above will be further discussed in the following chapters.

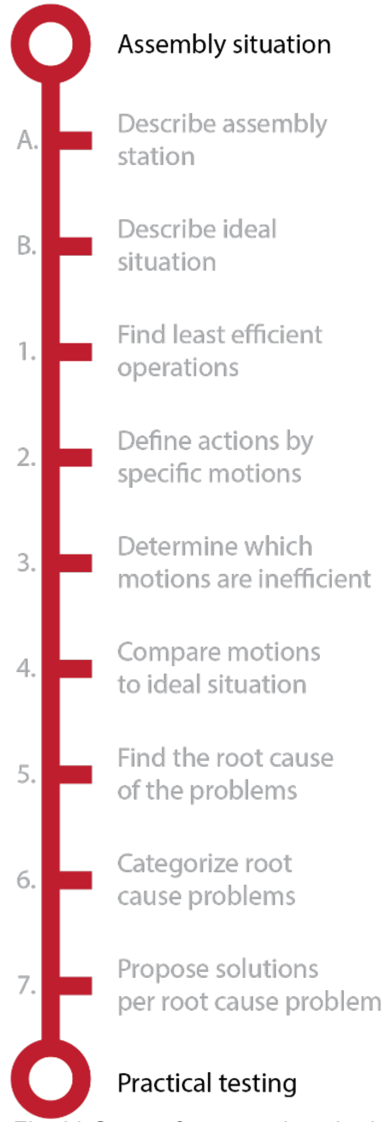

Fig. 32 Steps of proposed method.

5.2 Describe the assembly situation

Before the approach is explained, the assembly station and its aspects are defined in this chapter, figure 33.
The assembly station is defined clearly because of two reasons: It allows for concise locating of the problems and makes comparison to the ideal situation possible. An assembly station is defined as a location on the assembly line in which materials enter in a certain state and leave in a configuration which is closer to the completion of the bicycle, see figure 34.

Within this assembly station, there is an assembly situation. This assembly situation consists of the physical aspects in which the material in are reconfigured into the materials out such as the materials, tools, material holders, assembler and physical assembly line, figure 35. Within the assembly situation, operations are performed which reconfigure the material into the material out. In this case, an operation adds materials to the bicycle frame. For example, attaching the handlebars to the bicycle frame and front fork.

To perform an operation, multiple actions are performed, figure 36. These actions contribute to the operation, but do not necessarily add materials to the bicycle frame. In the example of attaching the handlebars to the bicycle frame and front fork, some of the actions are to walk towards the assembly rack, lift the handlebars, open the handlebars and reconfigure them. These actions can be broken down into specific movements, which are the building blocks of the assembly process. By comparing the specific movements to the ideal situation using the list of requirements, the problems of the assembly station become clear. The next chapter describes the ideal situation of such an assembly station.

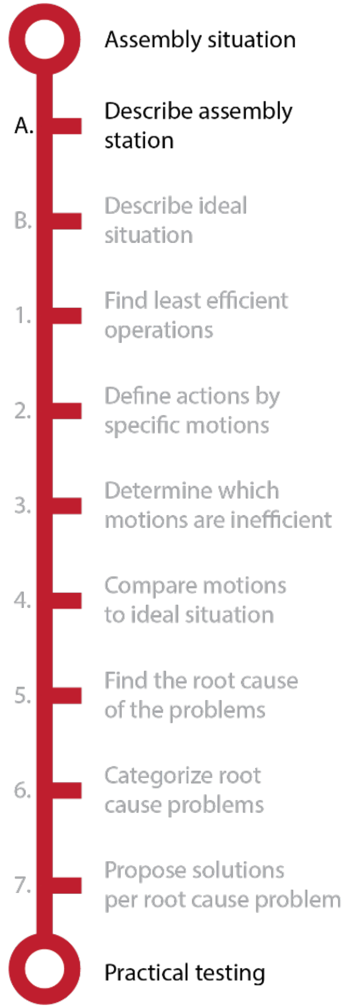

Fig. 33 Describeassemblystation.

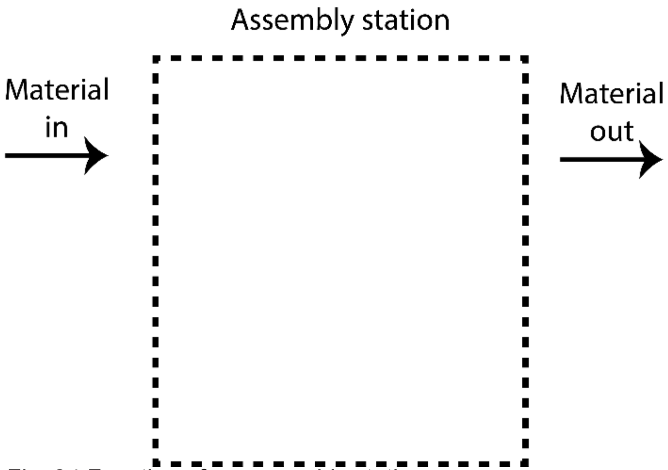

Fig. 34 Function of an assembly station.

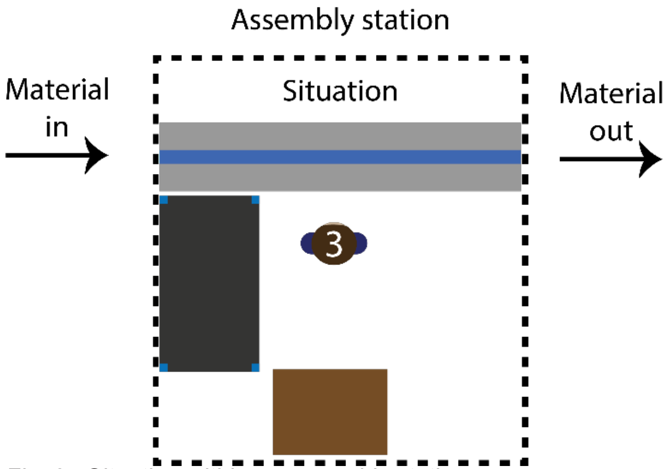

Fig. 35 Situation within an assembly station.

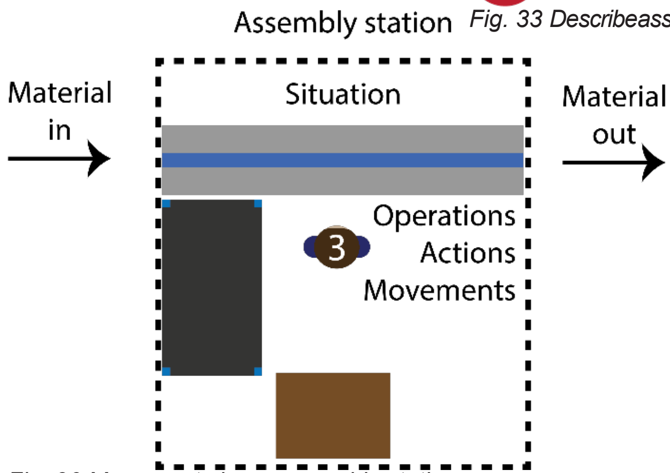

Fig. 36 Movements in an assembly station.

5.3 Describe the ideal situation

In the ideal assembly situation, as little time, energy and material is used to transform the material in into the material out. This is already discussed in the literature review chapter 3.2 Toyota Production System work categorization. An example is used to illustrate what is more ideal. This is the second preparation step of the investigation method, see figure 39.
In the example presented in figure 37, the assembler has to turn and reach for a material on the left of him during movement 1 and 2. After this assembly operation is completed, the assembler has to turn around, walk multiple steps, pick up a part, turn around again, walk multiple steps and complete the assembly operation, illustrated in movements 3 and 4. Since multiple movements are performed which the Toyota Production System would categorize as non-value-adding, these operations would not be very effective. In figure 38, a more ideal situation is presented, where the assembler must pick the part in front of him, perform the first assembly operation, pick the second part in front of him and complete the second assembly operation. This second situation does not require the assembler to turn or walk. Here, less assembly steps are performed which the Toyota Production System would categorize as Non-value-adding. This would be a more ideal situation since less time and energy is spent in transforming the material in into the material out.
Since the ideal situation is well defined but not well testable, the list of requirements is used to compare the movements to. Based on the violations of the list of requirements per movement, root cause analysis can be performed to identification the origin of the non-value-adding movements. This root cause analysis occurs in step 5 of the method sequence. Before that step is covered, the inefficient movements still need to be found.

The next chapter describes how to find the least efficient operations.

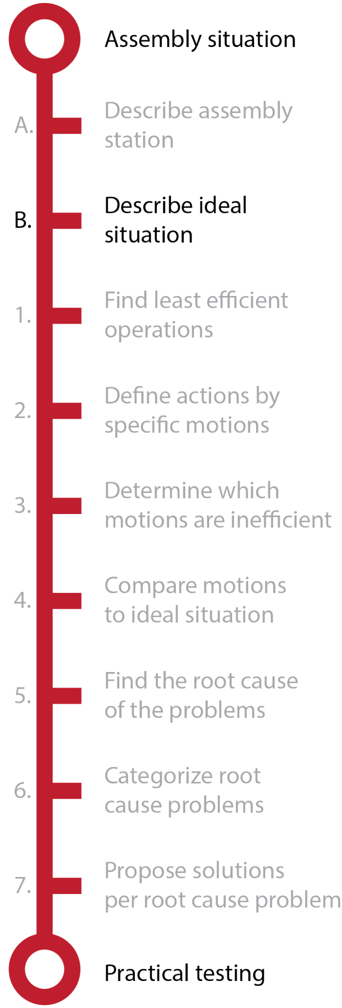

Fig. 39 Describe ideal situation.

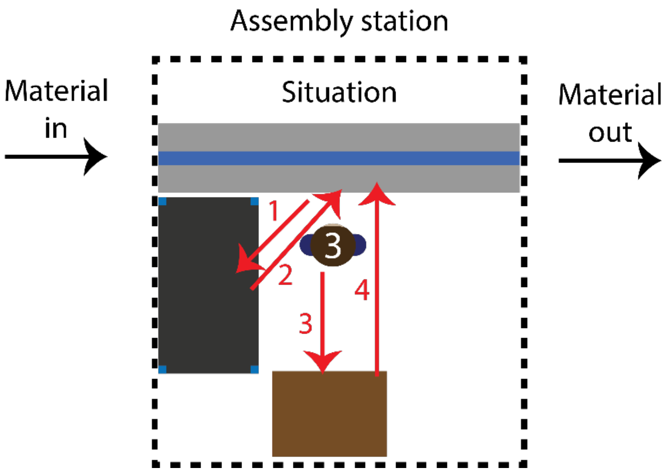

Fig. 37 Example of inefficient movements.

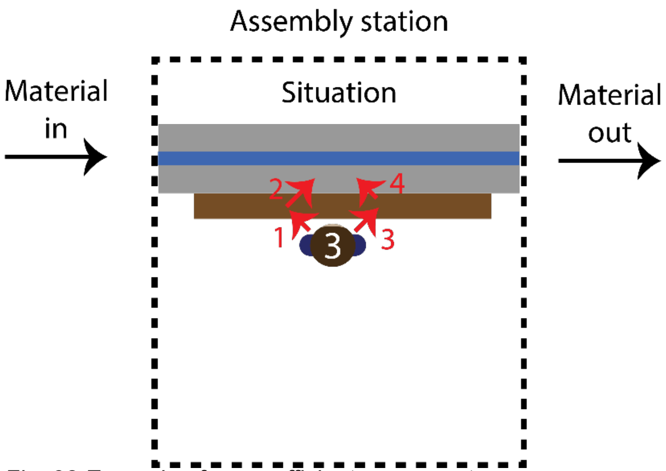

Fig. 38 Example of more efficient movements.

5.4 Find least efficient operations

Now that the assembly station and the ideal situation are defined, the investigation can be initiated. The first step is to determine which operations should be focussed on, figure 40. This is gained by analysing the video material. This initial video analysis consists of the following steps based on the approach detailed in chapter 3.2, Toyota Production System work categorisation:

1. Record all movements of the assembly operations of all assembly stations.
2. Categorize per second of footage if the movement on the screen is value-added-work or non-value-added work, figure 41.
3. Sort the assembly operations by seconds of non-value-added work.

The outcomes are the operations which should be focussed on, since the largest amount of time is spent on non-value-added work. Therefore, these operations are the largest time saving opportunities. It can also occur that a large amount of time is spent on a value-adding activity, but that the operation itself is wasteful. For such cases, the investigator must be vigilant and observe the video footage to understand the operation outside of the data sheet as well.

The other relevant aspects of the assembly line such as assembler workload, faulty bicycles and quality, the least inefficient operations can be investigated at a later stage in the process, since inefficiency of an operation can be connected with heavy assembler workload or movements which are hard to perform, therefore having high potential to cause damage to the bicycle. These aspects can also be noticed during this part of the video analysis, and a note can be made on the movement.

Once the assembly line operations are ordered on non-value-added work, the next step is to find out what makes these operations ineffective. This is done by defining the specific actions per assembly operations and of which movements these actions are constituted. To achieve this, MOST's naming method is applied to the selected assembly operations. This step is described in the next chapter.

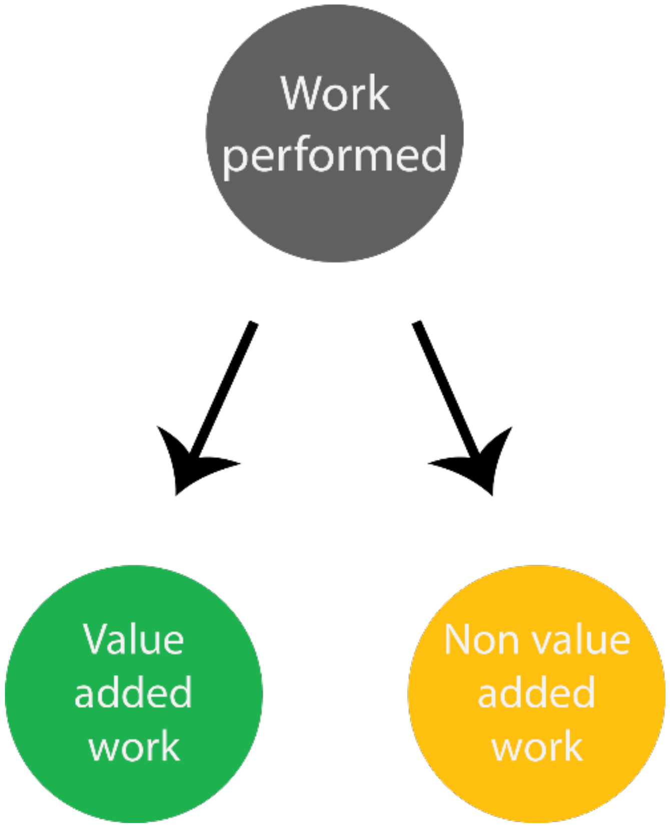

Fig. 41 Divide work into categories.

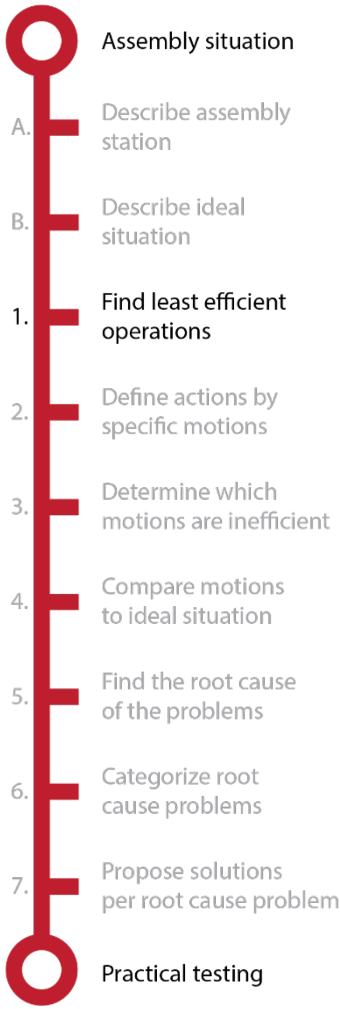

Fig. 40 Findleastefficientoperations.

5.5 Define actions by specific motions

As described in chapter 5.3 Describe assembly station, operations consist of actions which in turn consist of movements. In this step, the investigator further investigates the operation by determining which actions are performed and of which movements these actions consist (Figure 42). This will allow the investigator to determine what movements make the operation inefficient at the next step. This determination of the movements clearly records the movements that occur, allowing the investigator to compare the current situation with a proposed future situation.

To define an action, the following MOST standardized format is used. This standardized format serves as a guide but can be extended to facilitate actions which require additional aspects to clearly define the movements which happened. The standard format is (Zandin, 2003):

[Gain control][Object][From location][Placement][To location]

To explain how this standardized format is applied, an example is provided where an action is rewritten as a combination of movements using this format: “Bend forward for grabbing handlebars” becomes “Grasp handlebar by bending forward and reaching with left arm from handlebar supply rack”.

Since the assembly action is now defined by specific movements, the investigator can start identifying which movements are efficient and which are inefficient to determine which movements provide improvement opportunities. This is performed using the MOST analysis and time measurements, which the next chapter further elaborates on.

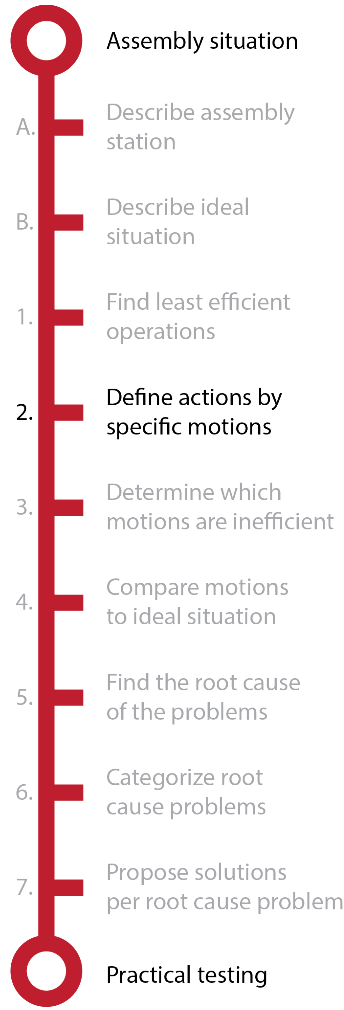

Fig. 42 Define actions by specific movements.

5.6 Determine which movements are inefficient

The movements are described according to the MOST standard format. They can now be categorized according to the BasicMOST methodology to estimate how long the activities take (figure 43).

This is done by translating the assembler's movements to the predetermined sets of movements using the BasicMOST lookup table (Zandin, 2003) as described in chapter 3.3. The specific actions are also divided into value-adding and non-value-adding actions per second of video footage. This gives us insight in which movements are necessary for the assembly of the bicycle and which movements can be reduced or removed.

Using the example from the previous page, the action "grab handlebar by bending forward and reach with left arm from handlebar supply" becomes:

A3 B0 G1, which is 40 * 0.036 = 1.44 seconds

Now that the time required per movement is estimated, the assembly movements can be compared to the ideal situation using the list of requirements in the next chapter.

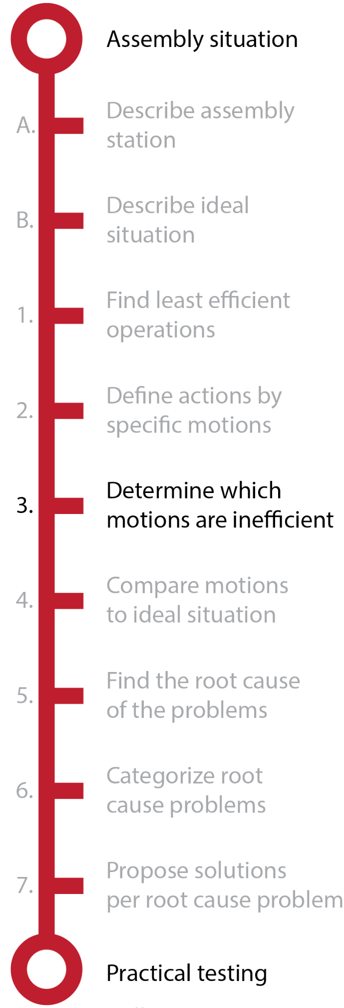

Fig. 43 Determine inefficient movements.

5.7 Define actions by specific motions

Now that the individual movements are specified, the problems of each movement must be identified, see figure 44. This is done by comparing the situation to the list of requirements, detailed in chapter 3.7 list of requirements. Once these problems are specified, it becomes possible to start the investigation on where these problems originate from. Comparison to the list of requirements also allows the investigator to compare the current situation to a proposed situation, to verify that the proposed improvements do not cause different problems.
The application of the list of requirements to the performed movements is illustrated using the first action of the handlebars fastening operation used in the previous chapter. The full list of violated requirements per investigated assembly operation is described in appendix H. As illustrated in table 5, the movements "turn around and take three steps" violate the requirements R2.1 and R2.27.

The next step in the solving process is to determine where these requirement violations originate from and will be described in the next chapter

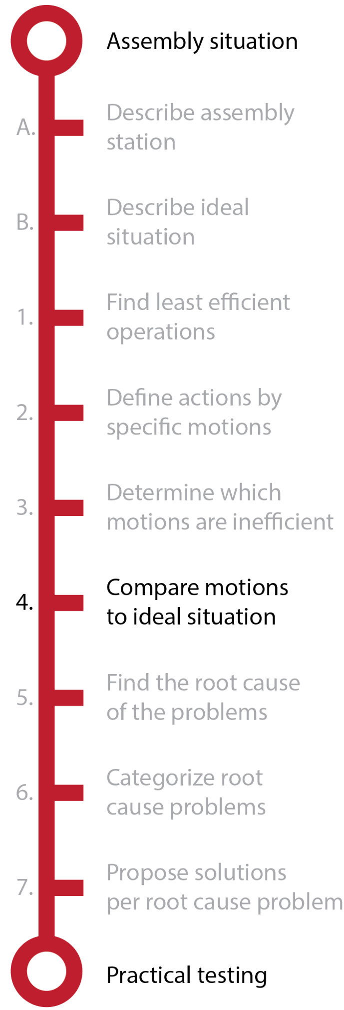

Fig. 44 Compare movements to ideal situation.

Actions	Movements	List of Requirements violations	Violated Requirements
Turn to grab handlebars	Turn around and take three steps to move from assembly location to handlebar supply rack.	R2.1	Assemblers must not be required to turn to pick up materials.
		R2.27	Assemblers must not be required to perform steps.

Table. 5 Example of violated requirements of one ssembly movement

5.8 Find the root cause of the problems

Now that the problems are defined for all assembly movements for the selected assembly improvement opportunities, the root causes of these problems must be found to solve these problems, figure 45. As described in chapter 3.5, The 5 Whys technique is applied to determine the root cause of the requirement violations. To illustrate this method, the requirement violations of the example of "turning to grab the handlebars" is investigated using the 5 whys method in table 6. The outcomes of the five whys analysis is described in chapter 5.5 and the full overview of the application of the technique is presented in appendix E. Now that the root causes of these List of Requirement violations are known, the next step is to categorize these root causes to provide the investigator guidance for finding solutions. This will be covered in the next chapter.

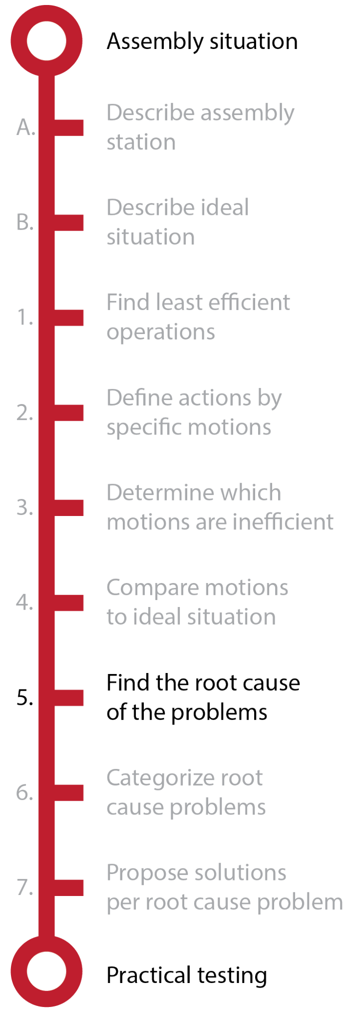

Fig. 45 Find the root cause of the problems.

R2.1 Assemblers must not be required to turn to pick up materials.
Why must the assembler turn to pick up materials?

The handlebar supply rack is behind the assembly location.

Why is the assembler supply rack behind the assembly location?

There is no space available in front of the assembler.
Why is there no space available in front of the assembler?

Smaller assembly materials are positioned in front of the assembler.

Why are there smaller assembly materials positioned in front of the assembler?
The multiple bicycles require multiple assembly materials for assembly.

Why are multiple bicycle assembly materials required for assembly?

The bicycles are designed to require multiple bicycle materials.

R2.27 Assemblers must not be required to perform steps.
Why must the assembler perform three steps to move to the handlebar supply rack?
The handlebar supply rack is positioned three steps away from the assembly location.
Why is the handlebar supply rack positioned three steps away from the assembly location?
Free workspace is required to open and restructure the handlebars.
Why is free workspace required to open and restructure the handlebars?
Opening and restructuring the handlebars requires wide arm movements to perform.
Why must the handlebars be opened and restructured?
The handlebars are provided in a closed and right-angled orientation by the handlebar sub- assembly department
Why are the handlebars provided in a closed and right-angled orientation by the handlebar sub-assembly department?
Because the sub-assembly department does not know that the handlebars. to be opened and reoriented.

Table. 6 The five why's method applied

5.9 Categorize the root cause problems

The application of the five whys to the performed movements results in a list of root causes, figure 46. Multiple of the investigated problems were found to originate from the same root causes. These root causes were found in multiple ways. The station layout was discovered by investigating the assembly line footage, where the materials were located behind the assembler. The possibilities of line balancing were discovered during the literature investigation. The other problem categories were found during the current state of the assembly line investigation. For example, the lack of part design was discovered during the semi-structured interviews, the interdepartmental communication was discovered during the context analysis and the ineffective work environment was discovered during the hands-on experience. To guide the investigator in finding the relevant solution for the root cause, the root causes are categorized in the following root cause types, figure 47. To illustrate this, the example of the root causes of turning to grab the handlebars are categorized below (table 7).

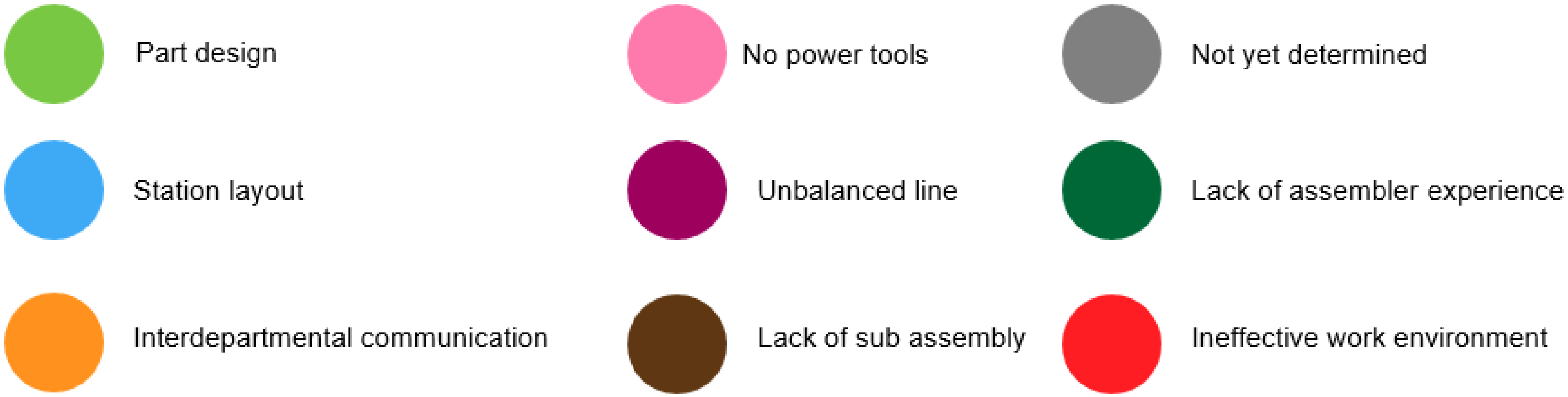

Fig. 47 Categories of root causes.

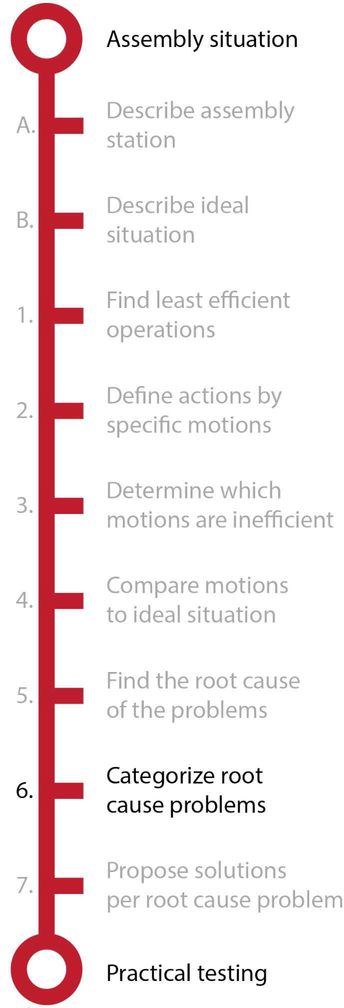

Fig. 46 Categorize root causes.

List of Requirement violation:	*R2.1 The assembler must not be required to turn to pick up materials.*
Root cause:	*The bicycles are designed to require multiple bicycle materials.*
Root cause category:	*Part design*
List of Requirement violation:	*R2.27 The assembler must not be required to perform steps.*
Root cause:	*The sub-assembly department does not know that the handlebars must be opened and reoriented.*
Root cause category:	*Interdepartmental communication*

Table. 7 Root causes of the violated requirements

5.10 Propose solutions per root cause problem

So far, the methods have changed assembly line video footage into categorized root causes. The step following this analysis process is to propose solutions for the root causes, see figure 48.

These solutions can be in various forms, ranging from every level of the organization. The knowledge, skill and experience of the investigator determines what the outcome of the solution finding step is. The book Kaizen assembly states that “Most non value-added work can be eliminated by using common sense.” (Ortiz, 2006)

To finish the example, we have been using so far, common sense solutions to root causes of the “Turn to grab handlebars” situation are depicted in table 8.

Method conclusion

This chapter has detailed the steps which the literature review provided to investigate the assembly line footage and structurally find solutions to the root cause problems of the assembly movements. As described in the prototyping chapter, this method should enable an investigator to investigate the assembly line using one sequence of methods backed by literature. To verify the feasibility of the method, the next chapter details three tests of the method to the assembly line footage. Here, it is investigated if the outcome of this method creates desirable outcomes for Accell. This is done by comparing the current situations on assembly times and violations of the list of requirements and comparing these to three improvements proposed by the method. The next chapter will describe the structural implementation of the method to three assembly line operations. For further clarification of the application of the method to the assembly line footage, the first test is described in detail in appendix J.

List of Requirement violation:	R2.1 The assembler must not be required to turn to pick up materials.
Root cause:	The bicycles are designed to require multiple bicycle materials.
Root cause category:	Part design
Common sense solution:	Investigate the possibilities of reducing the variety of assembly materials used over the various bicycle types. This can lead to reduction of assembly materials at the assembly line stations which frees up space to place assembly materials close to the assembly location. Other consequences of this type of action could be the reduction of warehouse volume, reduction of logistics complexity and allow standardization.

List of Requirement violation:	R2.27 The assembler must not be required to perform steps.
Root cause:	The sub-assembly department does not know that the handlebars must be opened and reoriented.
Root cause category:	Interdepartmental communication
Common sense solution:	Walk over to the sub-assembly department and discuss the possibilities of not closing and orienting the handlebars before transport, saving time and energy on both the assembly line and sub-assembly department side.

Table. 8 Common sense solutions to the found root causes

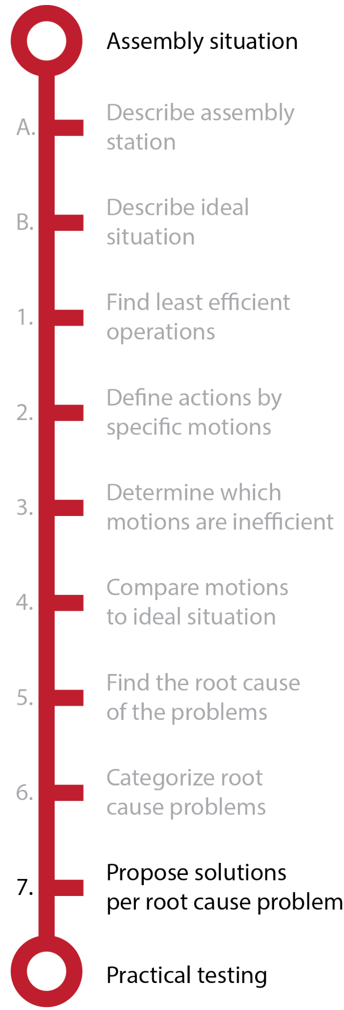

Fig. 48 Propose solutions to root causes.

The goal of this chapter is to test the feasibility of the method proposed in chapter 5. In the previous chapter, the 5 stations which contained the most non-value-adding time were analysed using the methods. From this top 5 stations, three proposed alterations to the assembly operations were tested. The testing was performed by recreating the assembly line stations, including the proposed changes. The assembly operations were then performed 10x while being captured on video. The video footage was then analysed to investigate whether the assembly time and number of violated requirements was changed. To create a fair comparison, a control group was created. This was done by recreating the original layout and performing the operation 10x in this situation as well. The locations of the materials at the current assembly line situation are estimated using standard size materials in the video footage as reference. Due to the covid-19 situation, it has not been possible to measure the assembly stations before testing.

To determine whether the method produces desirable outcomes for Accell, the impact of the assembly stations is measured. This is done measuring the differences in assembly time and the impact of the changes on Accell's five goals (efficiency, bicycle quality, costs, worker workload, faulty bicycle amount). The differences in assembly time are measured by calculating the assembly time differences from the video footage between the assembly line situation and the improvement proposal situation. The impact of the changes on Accell's five goals is determined by using the list of requirements as evaluation criteria for both scenarios.

Due to the covid-19 situation, on site testing was not possible. Therefore, practical testing of proposed solutions related to interdepartmental communication, bicycle design, line balancing was not possible. The proposed solutions which could be tested are depicted in table 9 in chapter 6.1.

6.1 List of test cases

To verify if the application of the proposed methods to the assembly line footage leads to a reduction of assembly time and improvement towards Accell's five goals, three tests are performed. To verify these two assumptions, four hypotheses were set up for the tests:

Null hypothesis aH0: The application of the proposed methods does not affect assembly time.

Research hypothesis aH1: The application of the proposed methods reduces assembly time.

Null hypothesis bH0: The application of the proposed methods does not reduce the amount of list of requirement violations.

Research hypothesis bH1: The application of the proposed methods reduces the amount of list of requirement violations.

The hypotheses are tested by creating the situations from the proposed solutions and compare them to the video footage assembly times of the assembly line and the list of requirements. The following practical tests are performed, table 9. The setups of the tests are displayed on the next pages.

Origin	*Root causes of Requirements violations*	*Problem category*	*Proposed solution*	*Testability*
Why's station 2	Handlebar rack placement	Workshop layout	Move handlebar rack closer to assembly location.	Yes
Why's station 3	Table wideness	Workshop design	Provide a platform under the frame location for assembly materials.	Yes
	Bins out of reach	Workshop layout	Place material bins on platform under frame location.	Yes
Why's station 5	Positioning pot of grease	Workshop layout	Place the grease pot close to the bolts bin.	Yes

Table. 9 Root causes of testable stations

6.2 Applying method to station 2: Secure handlebars

In this chapter, the application of the final method is described to the assembly line footage for the first assembly line improvement. The test which determines if the outcome is feasible is described in chapter 6.3.

1. Find the least efficient operation.
Station 2, secure handlebars has 3 seconds of value-added time and 26 seconds of non-value-added time. This makes this operation the least efficient operation at the assembly line.

2. Define actions by specific movements.
This operation consists of 13 movements, already described in appendix J.

3. Determine which movements are inefficient.
Based on the Toyota Production system work categorisation, the movements 2.9 and 2.12 add value to the bicycle. The other 11 movements are non-value-adding and are therefore considered inefficient, see figure 50.

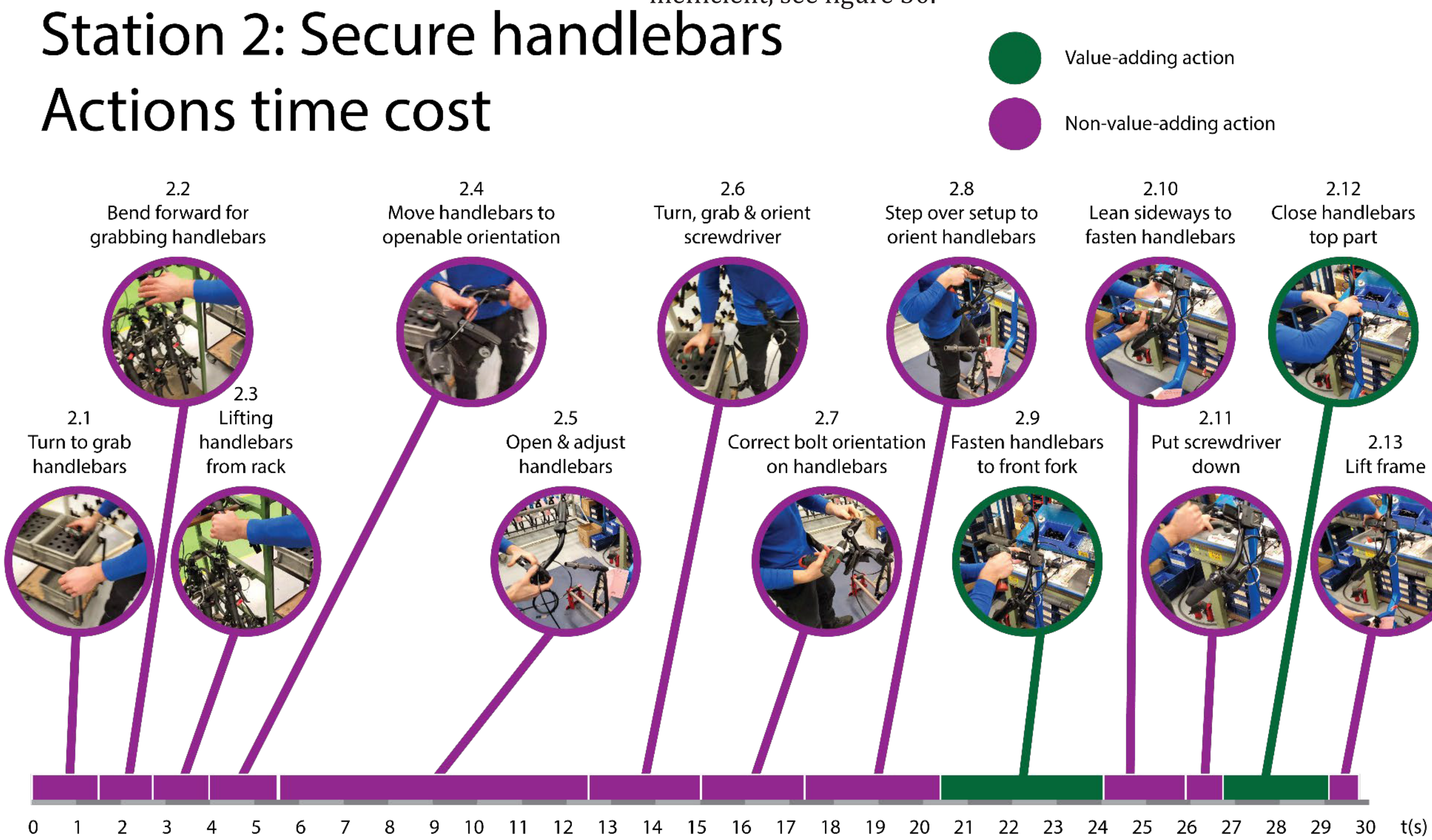

Fig. 50 Timeline of assembly movmements.

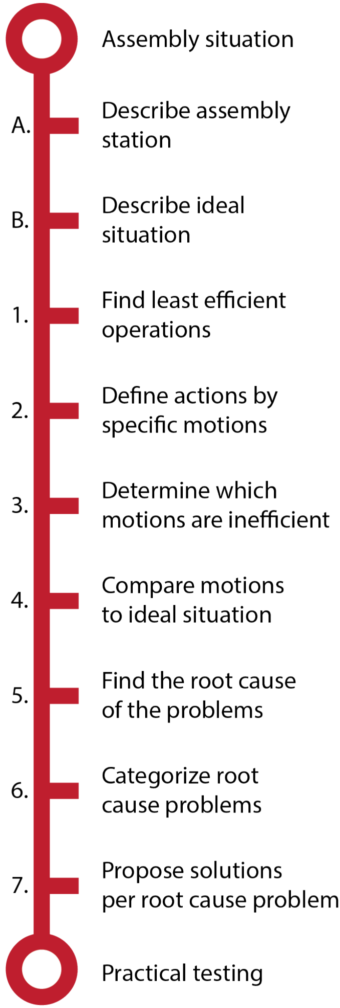

Fig. 49 Method steps.

4. Compare movements to ideal situation.
The movements are compared to the list of requirements, appendix K. The violated requirements per assembly operation are depicted in figure 52.

5. Find the root cause of the violated requirements.
The following root causes were found using the five why's on the violated requirements for the movements at station 2: secure handlebars.

- The bicycles are designed to require multiple bicycle materials. This causes the parts to be placed far apart, which causes the need to walk during movement 2.1, 2.4, 2.5, 2.6 and 2.8.
- The sub-assembly department does not know that the handlebars must be opened and reoriented. This causes the assembler to open the handlebars, which causes movement 2.4, 2.5, 2.6, and 2.7.
- The handlebar rack is placed on the far end of the assembly situation. This causes the need to walk and reach during movement 2.2, 2.4, 2.5, 2.6, 2.7, 2.8.
- The handlebar supply rack is designed to require lifting of the handlebars. This causes the need to lift the handlebars during movement 2.3.
- The material racks are positioned with the broad side to the assembler, allowing the assembler access to all available materials. This causes the need to bend forward during movement 2.2.
- The automated screwdriver must be inserted to the handlebars before orienting and this occurs in between the handlebar supply rack and the assembly location. This causes the need to move to a open area during movement 2.4, 2.5, 2.6 and 2.7.

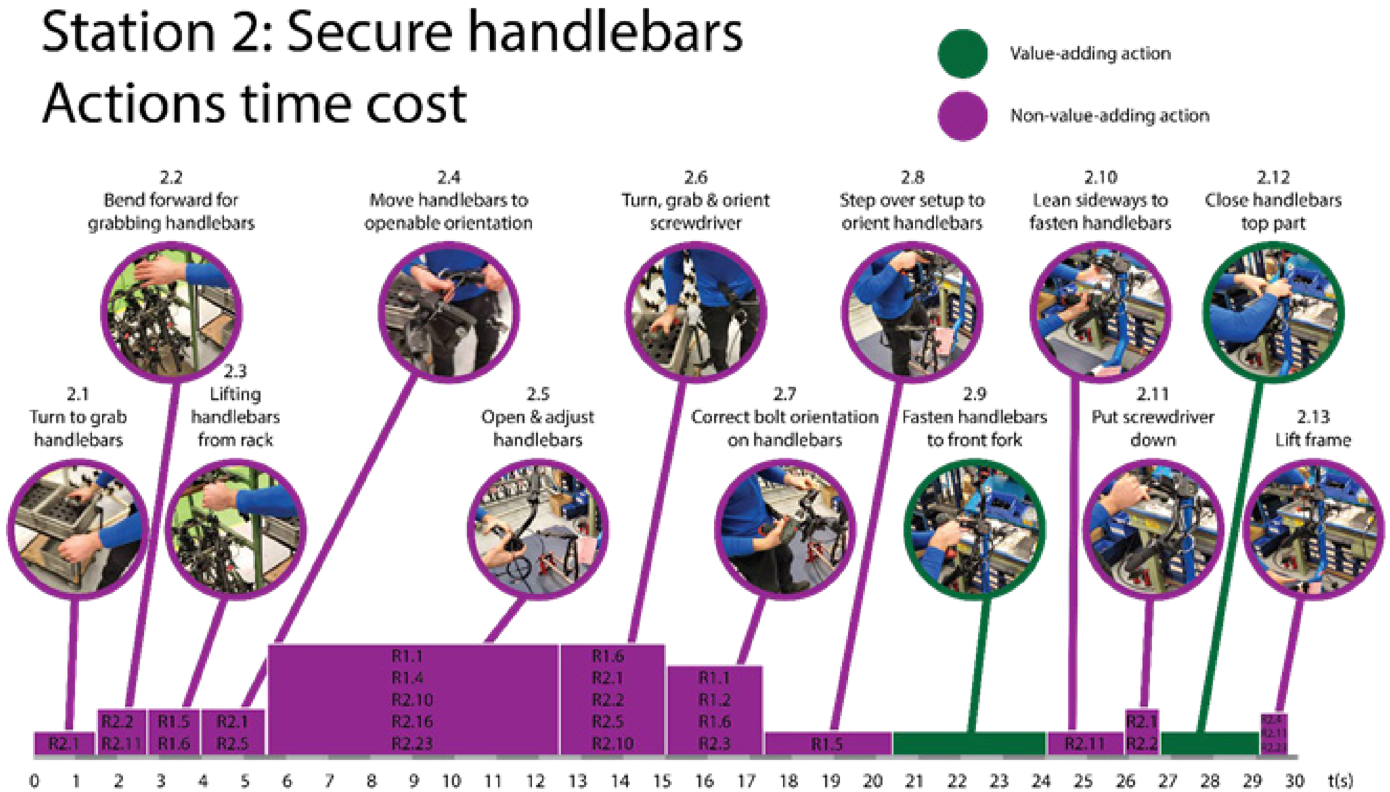

Fig. 52 List of requirement violations per assembly motion.

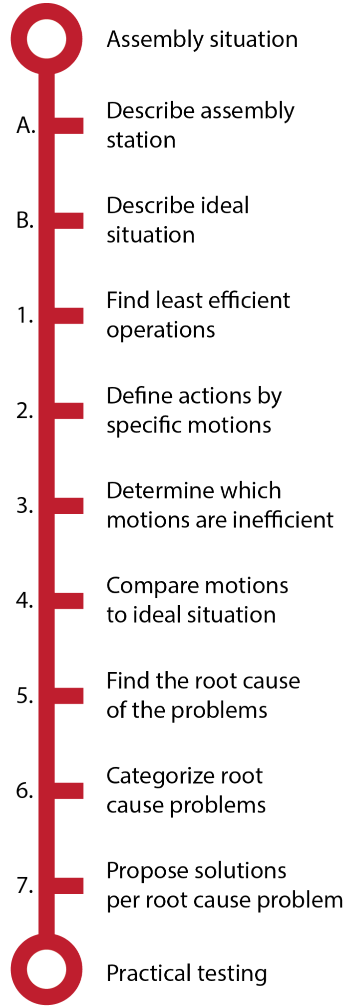

Fig. 51 Method steps.

6. Categorize the root causes of the violated requirements
The root causes were categorized according to step 6 as described in chapter 5.6. These findings are depicted in table 10.

7. Propose solutions per root cause problem
The solutions per root cause were proposed based on the common sense approach as described in chapter 5.7, These are depicted in table 11.

Practical testing
For practical testing during the covid-19 situation, the relocation of the handlebar rack was deemed testable using a simulated environment. The other proposed solutions are changes which either require being in the assembly hall or cooperating with the employees of Accell. Since that was not possible at the time, only the handlebar rack placement is fit for testing. The tests are described in chapter 6.3.

• Bicycle design	The bicycles are designed to require multiple bicycle materials.
• Interdepartmental communication	Because the sub-assembly department does not know that the handlebars must be opened and reoriented.
• Station layout	The handlebar rack is placed on the far end of the assembly situation.
• Workshop design	The handlebar supply rack is designed to require lifting of the handlebars.
• Workshop design	The material racks are positioned with the broad side to the assembler, allowing the assembler access to all available materials.
• Station layout	The automated screwdriver must be inserted to the handlebars before orienting and this occurs in between the handlebar supply rack and the assembly location

Table. 10 Categorizing the root causes of the violated requirements of station 2

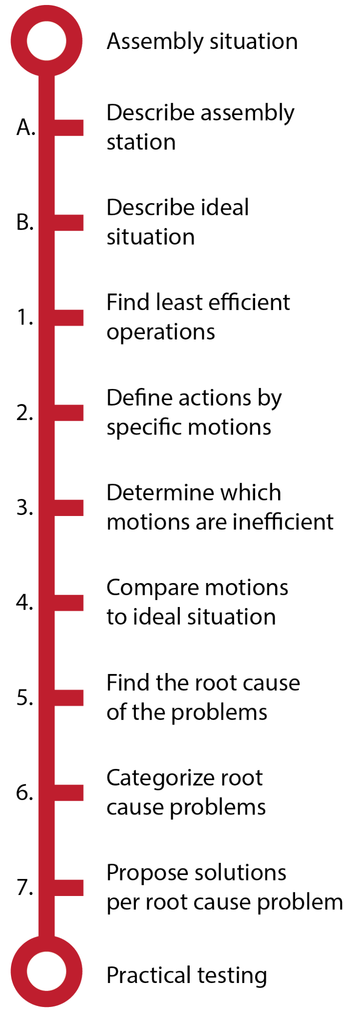

Fig. 53 Method steps.

Root causes of Requirements violations	*Problem category*	*Proposed solution*	*Testability*
Bicycle design causing multiple materials.	Bicycle design	Decrease material variety over bicycle models.	No
Handlebars provide closed and wrongly oriented	Interdepartmental communication	Ask handlebars department to not close and orient the handlebars.	No
Handlebar rack placement	Workshop layout	Move handlebar rack closer to assembly location.	Yes
Handlebar rack design	Workshop design	Change rack design so lifting handlebars is unnecessary.	No
Handlebar rack positioning broad side	Workshop design	Change rack design so handlebars can be picked from the side.	No

Table. 11 Solutions per root cause problem of station 2

6.3 Experiment planning station 2: Handlebar rack placement

This chapter details the setup of the test for the first proposed improvement of the final method's application to the assembly line footage. Testing the feasibility of the proposed improvement also influences the view of the viability of the method by providing data for the hypotheses stated in chapter 6.1.

Scope

The scope of this investigation is the part of station 2's fastening handlebar operation where the handlebar is grabbed from the material supply and positioned on the front fork for fastening. This requires 8 actions, which are described below and presented in a spaghetti diagram in figure 54. This operation was covered in chapter 5 as example.

Movements

2.1 Turn to grab handlebars	1.6 seconds
2.2 Bend forward for grabbing handlebars	1.1 seconds
2.3 Lifting handlebars from rack	1.2 seconds
2.4 Move handlebars to open-able orientation	1.5 seconds
2.5 Open & adjust handlebars	7.0 seconds
2.6 Turn, grab & orient automated screwdriver	2.4 seconds
2.7 Correct bolt orientation on handlebars	2.4 seconds
2.8 Step over setup to orient handlebars	3.1 seconds

Proposed improvement 1

Before the relocation of the handlebar rack can be tested, it is assumed that is possible that communication with the handlebars department leads to the provision of the handlebars in open orientation. This is predicted to eliminate actions 2.4, 2.5, 2.6 and 2.7, since these are required for the opening of the handlebars. The predicted resulting movements are presented in the spaghetti diagram of figure 55. To test this, the assembly situation is recreated, and the actions are performed with open handlebars as provided material. The situation with the open handlebars is assumed to have the following actions:

Action 2.1 Turning and taking three steps, one of which over the frame holder	1.6 seconds
Action 2.3 Lifting of the handlebars	1.2 seconds
Action 2.8 Taking two steps and one step over the frame holder	3.1 seconds

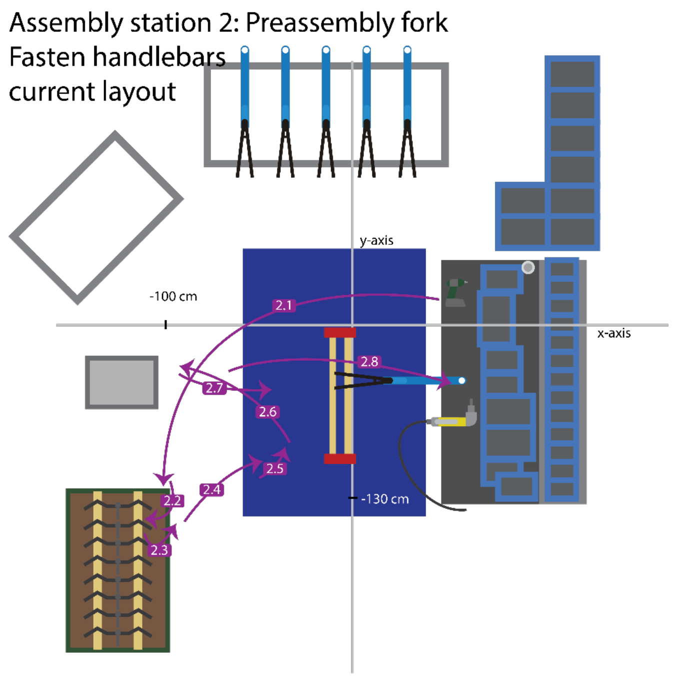

Fig. 54 Current movements at the assembly line.

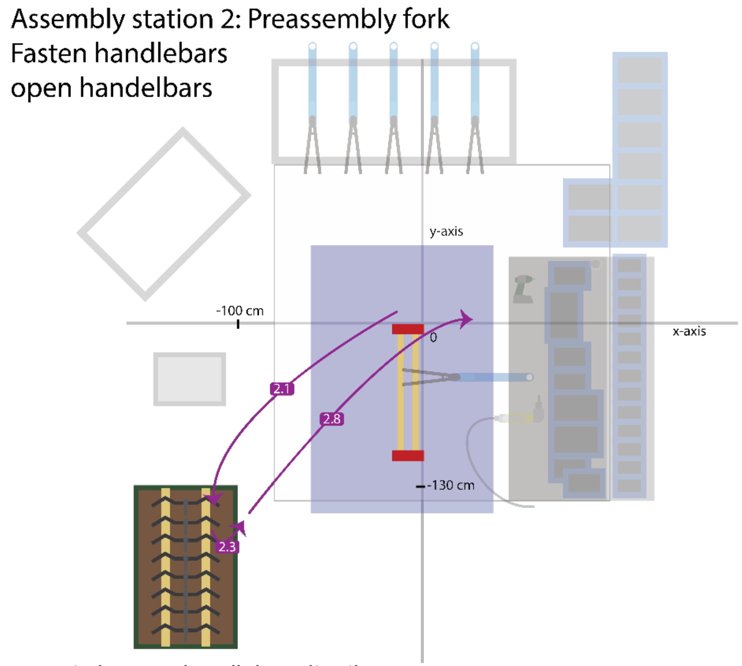

Fig. 55 Movements in open handlebar situation.

Layouts
The layout was also created and tested. Figure 56 also shows the location of the handlebar rack.

The current layout is:

Current handlebar rack location	x = - 100 cm	y = -130 cm
Altered handlebar rack location	x = - 70 cm	y = 0 cm

The location of x = -70 is applied so that the assembler has room available for placing the dummy saddle pin during another operation at this station, see chapter 2.2 for the details of the other operations at station 2.

Testing the main hypothesis at station 2
If the null hypotheses aH0 and bH0 were true, then the proposed improvements do not influence assembly time and do not reduce the amount of violations of the list of requirements.

If the research hypotheses aH1 and bH1 were true, then the proposed improvements must reduce assembly time and reduce the amount of violations of the list of requirements

To test these hypotheses in this situation, the following assumptions are tested for these assembly station layouts during test 1 and 2.

Test 1: open handlebars situation
aH0
A.1: Providing the handlebars in open orientation does not influence the time required to perform actions 2.1 to 2.8.
aH1
A.2: Providing the handlebars in open orientation reduces the time required to perform actions 2.1 to 2.8.
bH0
A.3: Providing the handlebars in open orientation does not influence the amount of list of requirement violations during actions 2.1 to 2.8.
bH1
A.4: Providing the handlebars in open orientation reduces the amount of list of requirement violations during actions 2.1 to 2.8.
aH0

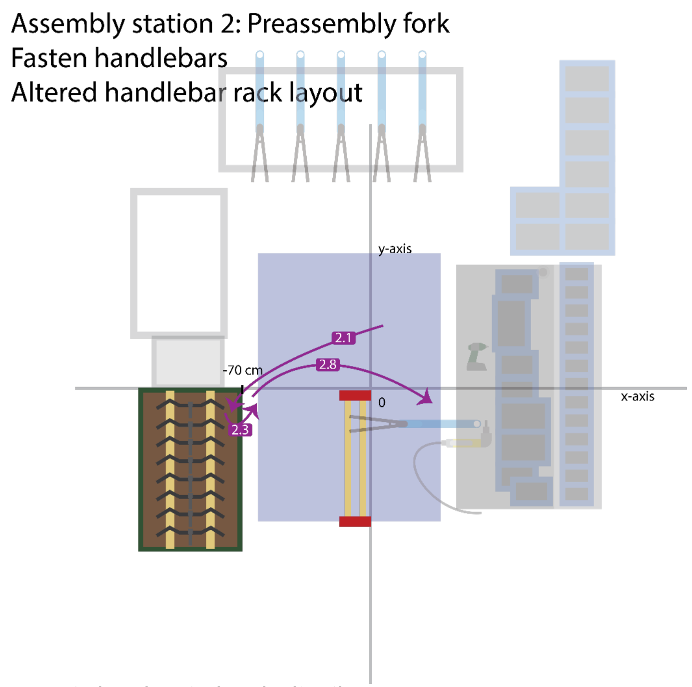

Fig. 56 Movements in relocated rack situation.

A.5: Relocating the handlebars rack from x = -100 cm and y = -130 cm to x = - 70 cm does not influence the time required to perform action 2.1 to 2.8.
aH1
A.6: Relocating the handlebars rack from x = -100 cm and y = -130 cm to x = - 70 cm and y = 0 cm reduces the time required to perform action 2.1 to 2.8.
bH0
A.7: Relocating the handlebars rack from x = -100 cm and y = -130 cm to x = - 70 cm and y = 0 cm does not influence the amount of list of requirement violations during actions 2.1 to 2.8.
bH1
A.8: Relocating the handlebars rack from x = -100 cm and y = -130 cm to x = - 70 cm and y = 0 cm reduces the amount of list of requirement violations during actions 2.1 to 2.8.

Figure 56 shows the proposed relocation of the handlebar rack.

Tests
The two tests which are performed are:
1. Perform the actions 10 times using the recreated current layout with open handlebars, captured on video.
2. Perform the actions 10 times using the altered handlebar rack layout with open handlebars, captured on video.
By simulating the current situation, the differences between the assembler and investigator are included in the data and can be corrected for. Unfortunately, the closed handlebar situation was not simulated for the secure handlebars experiments. The other experiments, however, did include the current situation simulations.

Schedule
1. Set up testing environment.
2. Ensure correct distances are practiced.
3. Perform the action 10 times on camera for the simulated current situation.
4. Perform the action 10 times on camera for the proposed situation.
5. Investigate differences in performance time.

Deliverables
Comparison of video footage, plot of data comparison plus discussion on results.

Tools
Table, two bars for frame-holder jig, two bars for handlebar rack, ABC Model bicycle materials, video camera, camera fixture.
The tools are described in chapter 6.8 and the testing setup is discussed in chapter 6.9. The next chapter details the second test of the method. There, the application of the improvement method is tested on station 3.

The outcomes of the tests are described in chapter 7, results. There, all three tests are compared on the performance of the individual assembly line improvement and the viability of the final method.

6.4 Applying the method for station 3: Prepare rear brake cable

This chapter details the second application of the final method to the assembly line footage. Here, the assembly line operation at station 3: prepare rear brake cable is investigated. The proposed improvement which the final method provided is tested in chapter 6.5.

1. Find the least efficient operation.

Station 3: prepare rear brake cable has 9 seconds of value-added work and 19 seconds of non-value-added work. This makes this operation the number 3 least efficient operation at the assembly line. The number two least efficient operation is lifting the bicycle frame from the manual to the automated assembly line, but improvements to that operation are not testable in the current covid-19 situation. Therefore, it is excluded from this project and the operation "Station 3: prepare rear brake cable" is tested instead.

2. Define actions by specific movements.

This operation consists of 8 movements for the fastening of the cable cover, cable ring, hollow bolt and rear brakes to the rear brake cable.

Movement 3.1 Drop cable cutter and turn towards bicycle frame
Movement 3.2 Turn and reach to grab cable cover
Movement 3.3 Turn and place cable cover over brake cable
Movement 3.4 Turn and grab ring and bolt
Movement 3.5 Turn and place ring and bolt over brake cable
Movement 3.6 Transfer cable from left to right hand
Movement 3.7 Turn and reach for rear brakes
Movement 3.8 Fasten rear brakes

3. Determine which actions are inefficient.

Based on the Toyota Production system work categorisation, the movements 3.3, 3.5 and 3.8 add value to the bicycle. The other 5 movements are non-value-adding and are therefore considered inefficient, see figure 58.

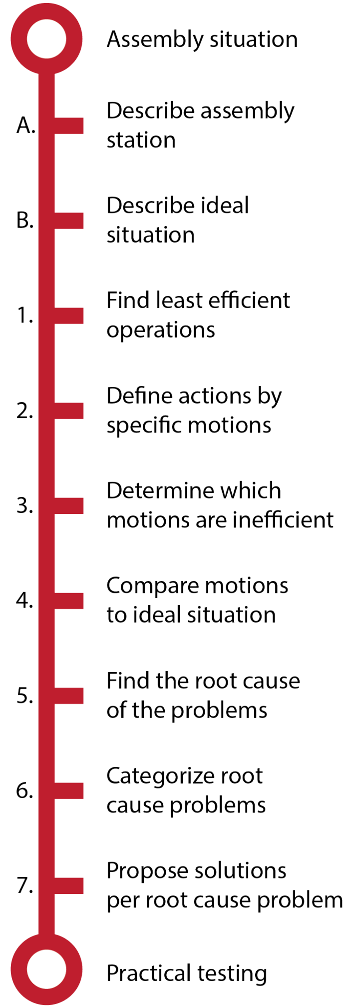

Fig. 57 Method steps.

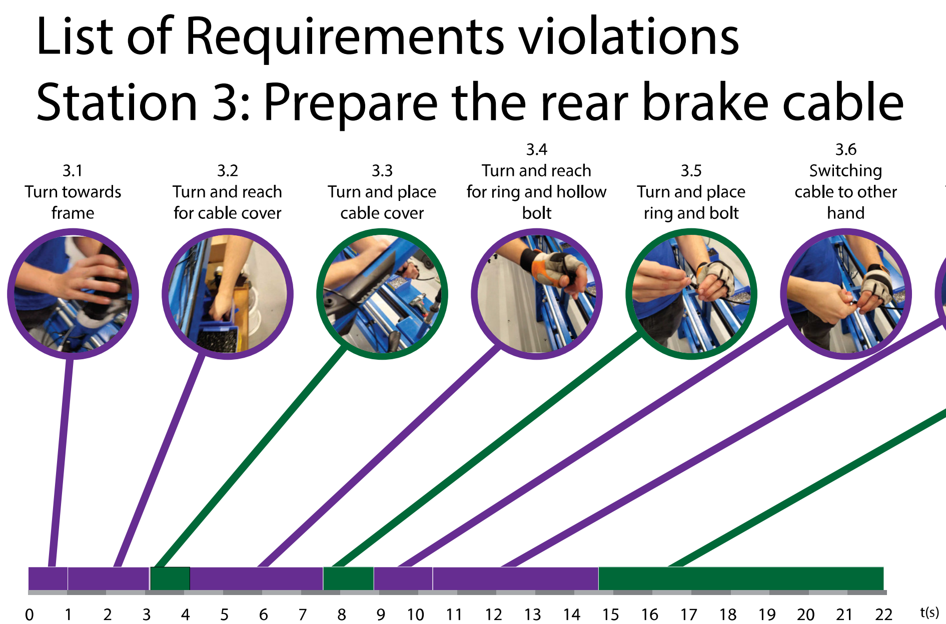

Fig. 58 Movement timeline of station 3: Prepare rear brake cable.

4. Compare movements to ideal situation.
The movements are compared to the list of requirements detailed in chapter 3.7. The violated requirements per assembly operation are depicted in figure 60.

5. Find the root cause of the violated requirements.
The following root causes were found for the violations of the requirements during the operation "Station 3: Prepare the rear brake cable":

• The wideness of the table would not allow the assembler to reach the assembly locations of the bicycle frame if placed in-between assembler and bicycle frame. This causes the turning which happens during movement 3.1, 3.2, 3.3, 3.4, 3.5, 3.7 and 3.8.
• The current design of the bin holder requires the assembler to pick materials from the opposite side to the assembly location. This also effects the turning and reaching which happen during movements 3.1, 3.2, 3.3, 3.4, 3.5, 3.7 and 3.8.

6. Categorize the root causes of the violated requirements.
The two root causes of the violations were categorized based on their origin type as described in chapter 4.10.
•Workshop design The wideness of the table would not allow the assembler to reach the assembly locations of the bicycle frame if placed in-between assembler and bicycle frame.
•Workshop layout The current design of the bin holder requires the assembler to pick materials from the opposite side to the assembly location, which is out of reach.

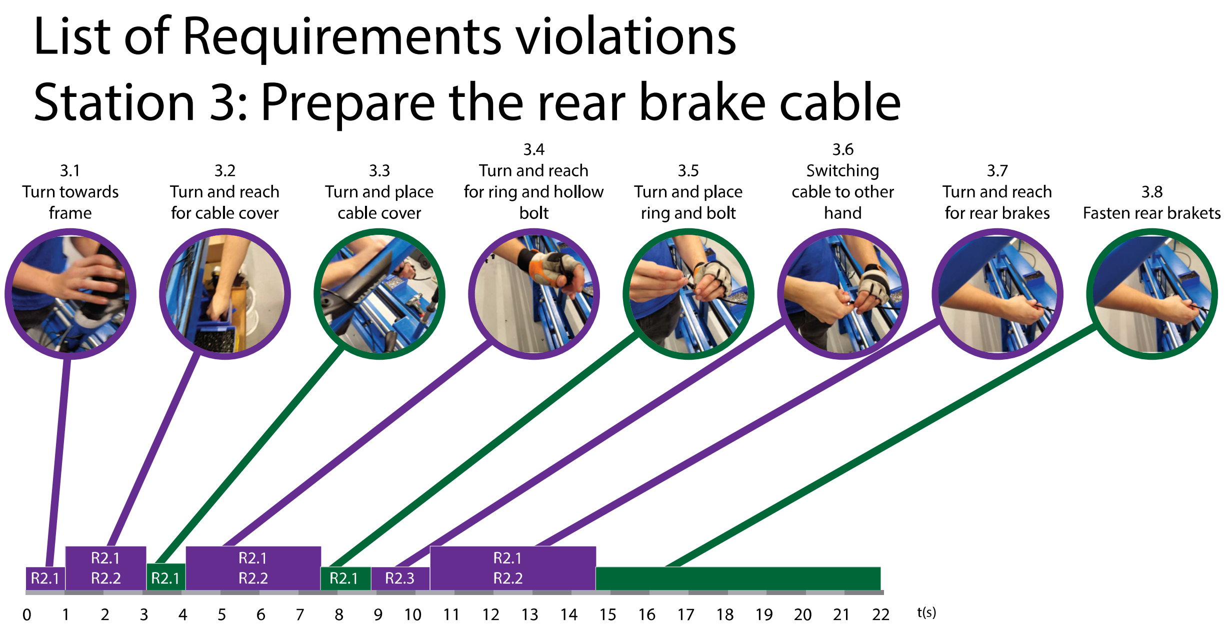

Fig. 60 Violated requirements per assembly movement.

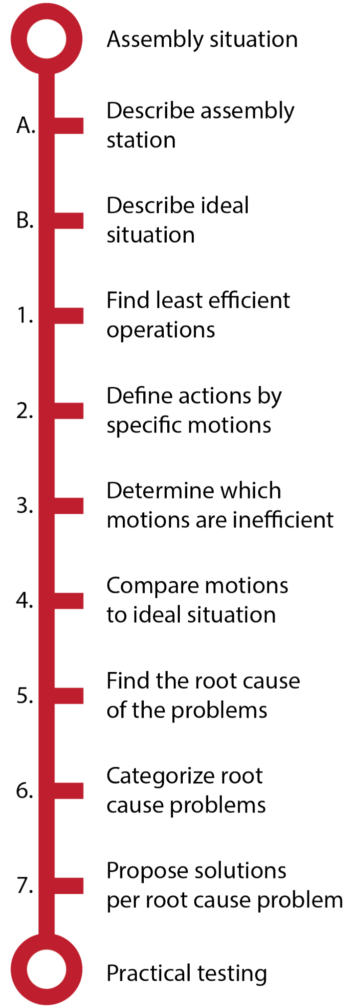

Fig. 59 Method steps.

7. Propose solutions per root cause problem.

Solutions for the categorized root causes were ideated using the common sense approach as described in chapter 4.11. The outcomes are described in table 12. Both solutions to the root causes can be tested by placing a platform with the materials under the assembly location. The experiments of this relocation are described in the next chapter, 6.5.

Root causes of Requirements violations	*Problem category*	*Proposed solution*	*Testability*
Table wideness	Workshop design	Provide a platform under the frame location for assembly materials.	Yes
Bins out of reach	Workshop layout	Place material bins on platform under frame location.	Yes

Table. 12 Root cause of violated requirements station 3

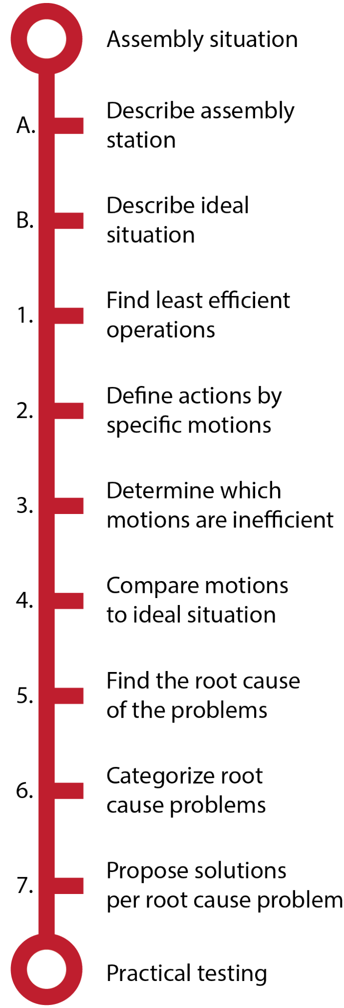

Fig. 61 Method steps.

6.5 Experiment planning station 3: Prepare rear brake cable

In this chapter, the impact of the second assembly line improvement proposed by the final method is investigated on assembly time and list of requirement violations. The outcomes of this investigation are described in chapter 7, results.

Scope
At station 3, one of the operations is to prepare a brake cable for fastening to the rear brakes, which requires eight actions. For this investigation, we focus on the bulk materials, which are processed between action 3.1 and 3.5. These are described below and visualised in figure 62 using a spaghetti diagram.

Movements

Movement 3.1	Drop cable cutter and turn towards bicycle frame	1.0 seconds
Movement 3.2	Turn and reach to grab cable cover	2.2 seconds
Movement 3.3	Turn and place cable cover over brake cable	0.9 seconds
Movement 3.4	Turn and grab ring and bolt	3.4 seconds
Movement 3.5	Turn and place ring and bolt over brake cable	1.3 seconds
Movement 3.6	Transfer cable from left to right hand	1.5 seconds

Proposed improvements
The proposed improvement is to relocate the material bins from behind the assembler to the front of the assembler. This would eliminate the turning during the actions 3.2, 3.3, 3.4, 3.5, lowering the time spent on these actions from 9 to 4.5 seconds. This proposed layout is provided using a spaghetti diagram in figure 63 and the specific locations are described below. The location of the materials for each situation is described below.

Layouts
Current layout (figure 62)

Cable cover bin	x = -150 cm	y = -20 cm	z = 75 cm.
Ring bin	x = -150 cm	y = -35 cm	z = 75 cm.
Bolt bin	x = -150 cm	y = -50 cm	z = 75 cm.

Relocated layout (figure 63)

Cable cover bin	x = -29 cm	y = -7.5 cm	z = 77 cm.
Ring bin	x= -29 cm	y = 22.5 cm	z = 77 cm.
Bolt bin	x= -29 cm	y = 7.5 cm	z = 77 cm

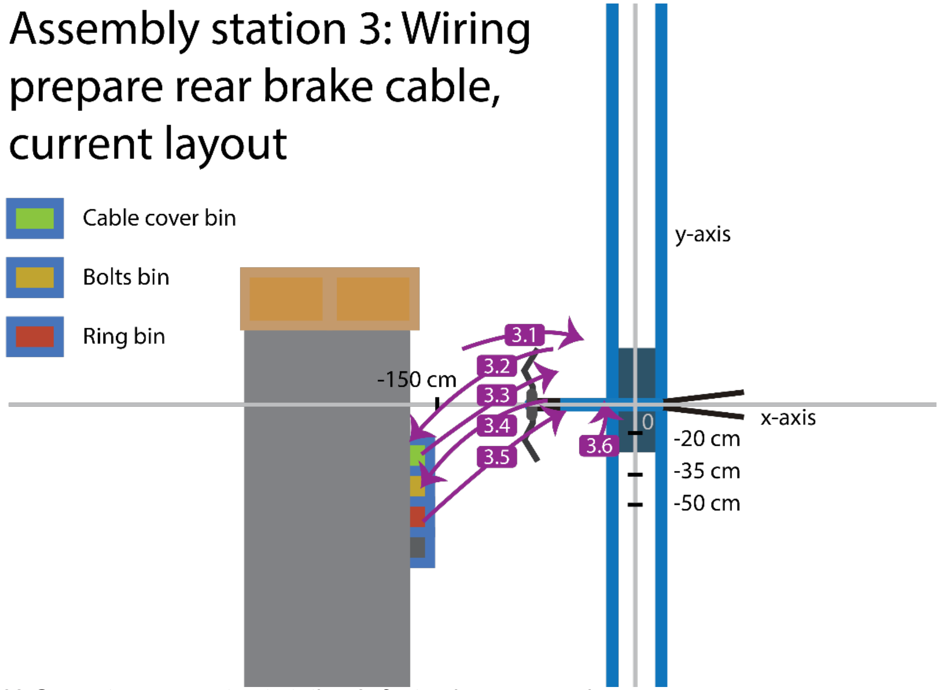

Fig. 62 Current movements at station 3: fasten luggage carrier.

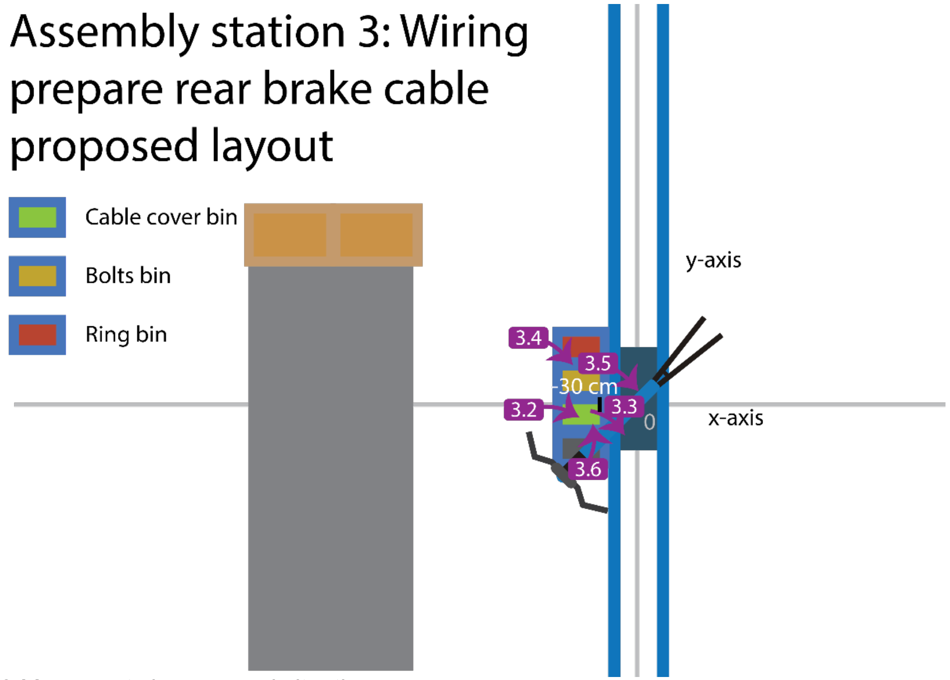

Fig. 63 Movements in proposed situation.

Tests

The prediction was tested by locally creating both situations and performing the actions 10 times while capturing the actions on camera. The impact of the relocation was measured by comparing both videos to the data from the assembly line footage. By simulating the current situation, the differences between assembler and investigator are included in the data and can be corrected for.

Testing the main hypothesis at station 3: prepare rear brake cable To test the main hypotheses in this situation, the following assumptions are tested.

Test 3: relocation the material bins

aH0

A.9: Relocating the material bins from x = -150 cm and y = -20/-35/-50 cm to x = -30 cm and y = 22.5/7.5/-75 cm does not influence the time required to perform action 3.1 to 3.5.

aH1

A.10: Relocating the material bins from x = -150 cm and y = -20/-35/-50 cm to x = -30 cm and y = 22.5/7.5/-75 cm reduces the time required to perform action 3.1 to 3.5.

bH0

A.11: Relocating the material bins from x = -150 cm and y = -20/-35/-50 cm to x = -30 cm and y = 22.5/7.5/-75 cm does not influence the amount of list of requirement violations during actions 3.1 to 3.5.

bH1

A.12: Relocating the material bins from x = -150 cm and y = -20/-35/-50 cm to x = -30 cm and y = 22.5/7.5/-75 cm reduces the amount of list of requirement violations during actions 3.1 to 3.5.

Schedule

The schedule for the tests is as follows:

1. Set up testing environment.
2. Ensure correct distances are practiced.
3. Perform the action 10 times on camera for the simulated current situation.
4. Perform the action 10 times on camera for the proposed situation.
5. Investigate differences in performance time.

Deliverables

The deliverables for these tests are:

- Comparison of video footage
- Plot of data comparison
- Outcomes description

Tools

Table, four material bins, brake cable bolts in bulk, brake cable rings in bulk, brake cable covers in bulk, ABC Model frame, bicycle assembly setup. The tools are described in chapter 6.8 and the testing setup is discussed in chapter 6.9. The next chapter details the third test of the investigation method. There, the application of the method on station 5 is detailed.

6.6 Applying the method for station 5: Fasten the luggage carrier

1. Find the least efficient operation.
Station 5: fasten the luggage carrier has 13 seconds of value-added work and 18 seconds of non-value-added work. This makes this operation the number 4 least efficient operation at the assembly line. The number five least efficient operation is installing the front mudguard at station 6. Improvements to that operation are not testable in the current covid-19 situation. Therefore, it is excluded from this project and the operation "Fasten the luggage carrier" at station 5 is the last operation that is being tested.

2. Define actions by specific movements.
This operation consists of 14 movements for the fastening of the luggage carrier.

Movement	5.1	Turn to grab bolt.
Movement	5.2	Grab bolt.
Movement	5.3	Reach to grease bolt.
Movement	5.4	Turn to orient bolt in luggage carrier.
Movement	5.5	Turn to grab and orient automated screwdriver.
Movement	5.6	Insert bolt and screwdriver in luggage carrier.
Movement	5.7	Orient and reorient bolt, screwdriver and luggage carrier.
Movement	5.8	Screw-driving.
Movement	5.9	Reorient bolt.
Movement	5.10	Screw-driving.
Movement	5.11	Turn, grab and orient bolt on screwdriver.
Movement	5.12	Reach to grease bolt.
Movement	5.13	Turn to orient bolt in luggage carrier.
Movement	5.14	Screw-driving.

3. Determine which movements are inefficient.
Based on the Toyota Production system work categorisation, the movements 5.8, 5.10 and 5.14 add value to the bicycle. The other 11 movements are non-value-adding and are therefore considered inefficient, see figure 65.

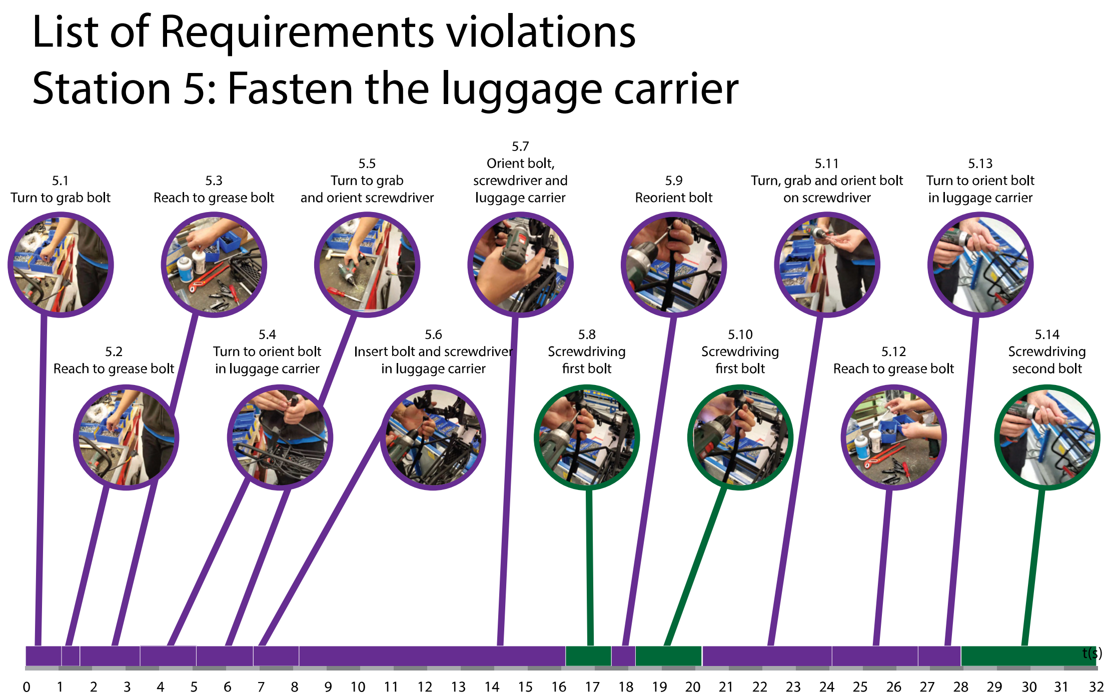

Fig. 65 Assembly time per movement at station 5: Fasten the luggage carrier.

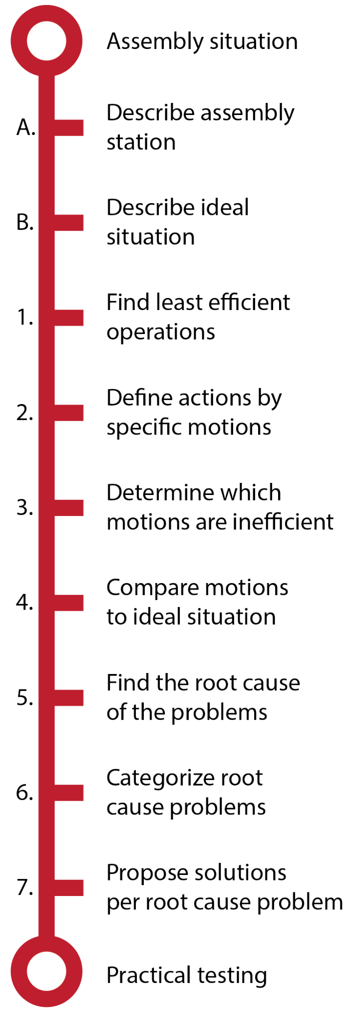

Fig. 64 Method steps.

4.Compare movements to the ideal situation.
The 14 assembly movements are compared to the ideal situation using the list of requirements. The violated requirements are displayed in figure 66.

5. Find the root cause of the violated requirements
To determine the root cause of the violated requirements, the five whys are applied to the violations of the list of requirements. The outcome of this investigation is the following list of root causes:

- The luggage carrier is designed too broad to fit in the frame without adjustments. This causes the need to re-adjust and reorient the luggage carrier during movement 5.7, 5.9, and 5.10.
- The luggage carrier cannot rest on the frame during assembly, therefore multiple hands are required during fastening. This causes the need to readjust the luggage carrier, bolt and automated screwdriver during movement 5.6, 5.7 and 5.9.
- The pot of grease is positioned so that the assembler must reach over the luggage carrier before greasing a bolt. This causes the need to extend the arm during movement 5.2 and 5.12.

6. Categorize the root causes of the violated requirements
The root causes are categorized based on the origin types as described in chapter 5.9. The result of this categorization is depicted in table 13. Based on this categorization, the investigator is guided in the solution direction during the next step.

Bicycle design	The luggage carrier is designed too broad to fit in the frame without adjustments
Bicycle design	The luggage carrier cannot rest on the frame during assembly.
Workshop layout	The pot of grease is positioned so that the assembler must reach over the luggage carrier before greasing a bolt.

Table. 13 Categorization of the root causes

List of Requirements violations
Station 5: Fasten the luggage carrier

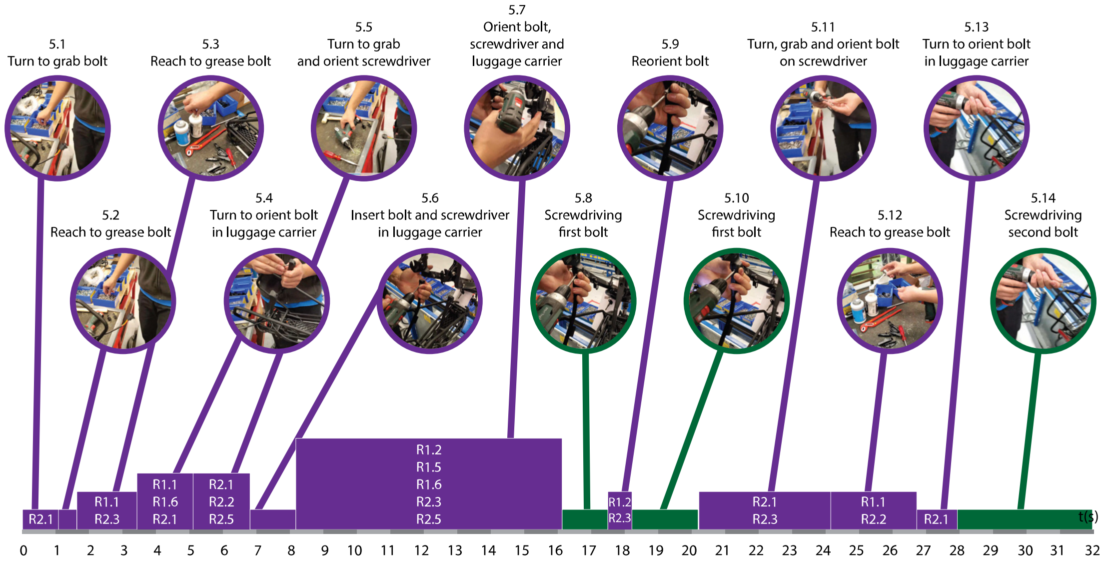

Fig. 67 Overview of requirement violations per movement.

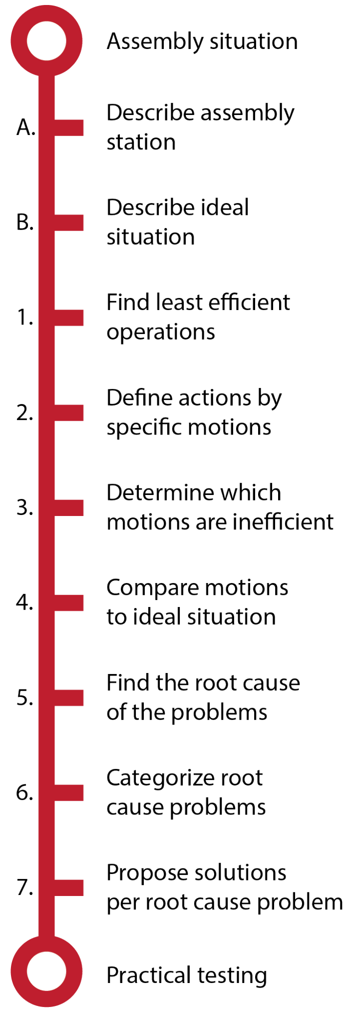

Fig. 66 Method steps.

7. Propose solutions per root cause problem.
Now that the root causes of the list of requirement violations are known and categorized, the common sense approach is used to come to solutions per root cause.

The proposed solutions per root cause are depicted in table 14. The bicycle design proposals are based on the current state of the bicycle in which the assembler must hold and compress the luggage carrier while fastening the first bolt. If the extension width of the luggage carrier would be changed, the luggage carrier would fit the frame. Then, the assembler would no longer be required to compress the luggage carrier during the fastening of the first bolt. If the frame would provide some way to rest the luggage carrier on during fastening of the first bolt, the assembler would not be required to lift the handlebars during fastening. The third proposed solution is to change the location of the grease pot. If the pot would be located closer to the bolts bin, the assembler would not be required to extend the arm when greasing the bolt. Since the first two proposed solutions cannot be tested in the covid-19 situation due to required cooperation, the third proposed improvement is tested. This test is described in the next chapter.

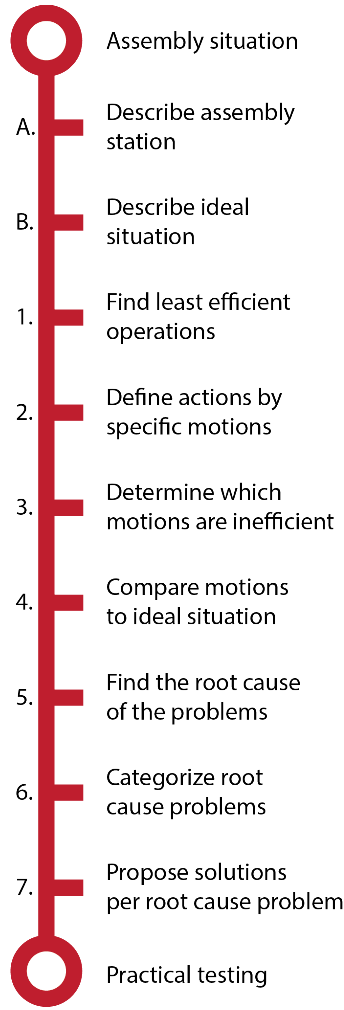

Fig. 68 Method steps.

Root causes of Requirements violations	*Problem category*	*Proposed solution*	*Testability*
Luggage carrier lack of design for assembly	Bicycle design	Change the frame so the luggage carrier can rest on it during fastening.	No
Luggage carrier does not fit frame bracket	Workshop layout	Change the luggage carrier's extensions width.	No
Positioning pot of grease	Bicycle design	Place the grease pot close to the bolts bin.	Yes

Table. 14 Root causes of violated requirements of station 5

6.7 Experiment planning Station 5: Fasten the luggage carrier.

In this chapter, the impact of the third assembly line improvement proposed by the final method is investigated on assembly time and list of requirement violations. The outcomes of this investigation are described in chapter 7, results.

Scope

The scope of this investigation is to determine if the location of the grease pots influences the assembly time between movement 5.1 and 5.4. The current layout of the assembly line and the proposed layout is depicted in figure 69 and 70 using spaghetti diagrams.

Actions

The actions depicted in figure 69 are:

- 5.1 Turn to grab bolt 1.2 seconds
- 5.2 Grab bolt 0.4 seconds
- 5.3 Reach to grease bolt 1.9 seconds
- 5.4 Turn to orient bolt in luggage carrier 1.6 seconds

Proposed improvement

The proposed improvement is to relocate the grease pot. This would eliminate reaching during action 5.3, lowering the spent time on this action by 1 second. The change in grease pot location is described below.

Layouts

Current layout (figure 69)

Grease pot	x = - 150 cm	y = - 40 cm
Bolt bin	x = -110 cm	y = 50 cm

Proposed layout (figure 70)

Grease pot	x = -120 cm	y = 40 cm
Bolt bin	x = -110 cm	y = 50 cm

Tests

Like the investigation in chapter 6.3, the relocation of the grease pot was tested by locally creating both situations and performing the actions 10 times while capturing the actions on camera.

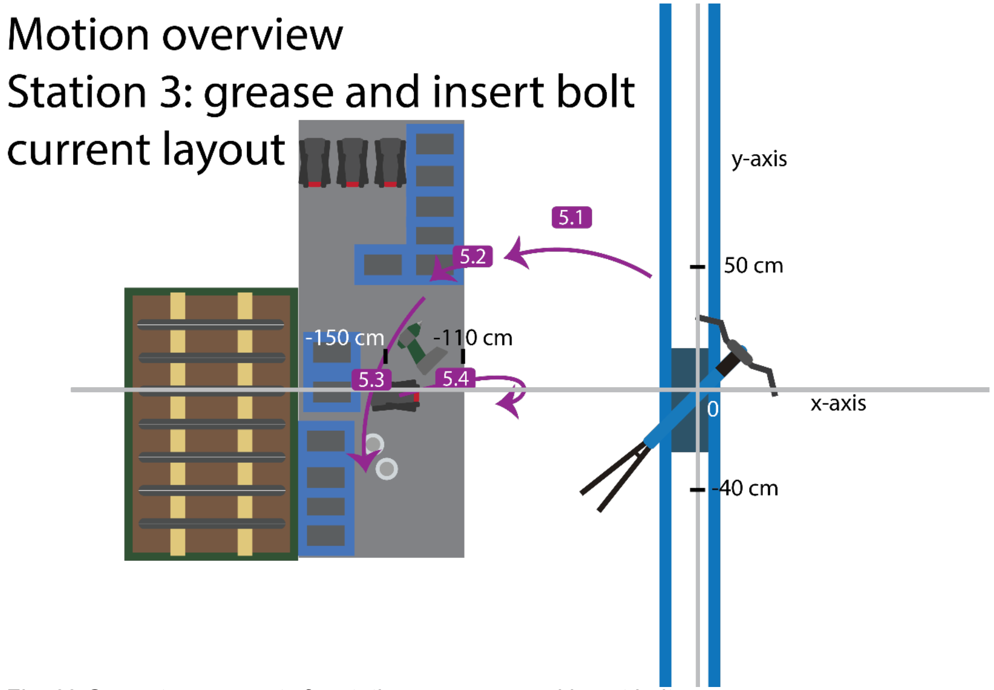

Fig. 69 Current movements for station 5: grease and insert bolt.

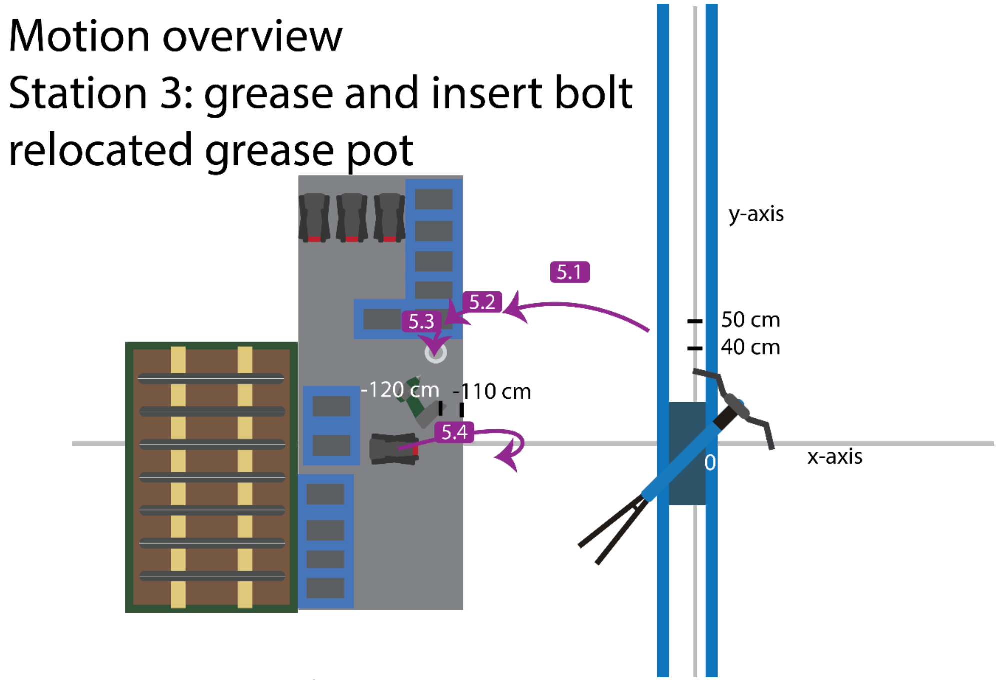

Fig. 70 Proposed movements for station 5: grease and insert bolt.

The impact of the relocation was measured by comparing both videos to the data from the assembly line footage. By simulating the current situation, the differences between the assembler and investigator are included in the data and can be corrected for.

Testing the main hypotheses at station 5: relocating the grease pot
To test the main hypotheses at station five, the following assumptions are tested.

Test 4: Relocating the grease pot
aH0
A.13: Relocating the grease pot from x = -150 cm and y = -40 cm to x = - 120 cm and y = 40 cm does not influence the time required to perform action 5.1 to 5.4.
aH1
A.14: Relocating the grease pot from x = -150 cm and y = -40 cm to x = - 120 cm and y = 40 cm reduces the time required to perform action 5.1 to 5.4.
bH0
A.15: Relocating the grease pot from x = -150 cm and y = -40 cm to x = - 120 cm and y = 40 cm does not influence the amount of list of requirement violations during actions 5.1 to 5.4.
bH1
A.16: Relocating the grease pot from x = -150 cm and y = -40 cm to x = - 120 cm and y = 40 cm reduces the amount of list of requirement violations during actions 5.1 to 5.4.

Schedule
The schedule for the tests is as follows:

1. Set up testing environment.
2. Ensure correct distances are practiced.
3. Perform the action 10 times on camera for the simulated current situation.
4. Perform the action 10 times on camera for the proposed situation.
5. Investigate differences in performance time.

Deliverables
The deliverables from the test are:

- Comparison video footage compilation
- Plot of data comparison
- Outcomes description

Tools
The tools used for testing are:

Table, grease pot, material bin, luggage carrier bolts in bulk, ABC Model bicycle, ABC Model assembly setup, Luggage carrier.

The materials used to execute the assembly line improvement testing are further described in the next chapter, 6.8. The set up is described in chapter 6.11.

6.8 Materials

The materials for the experiments were sourced locally due to the current covid-19 situation. To simulate the assembly line situation, a rotatable dummy saddle pin was built on which the bicycle frame can rest. This enables the assembly operations to be performed upside down to mimic the assembly line situation. The setup is depicted in figure 71 and 72.

The assembly lines use material bins to hold bulk material. For the test, 14.5 x 13.5 x 24 cm bins are used as depicted in figure 73. Figure 73 also depicts the bicycle assembly materials, which consist one ABC Model bicycle is used along with 20 times all bulk fastening materials. For the material table, two wooden trestles and a wooden plank were used. The height of the table was 77 cm high, see figure 74.

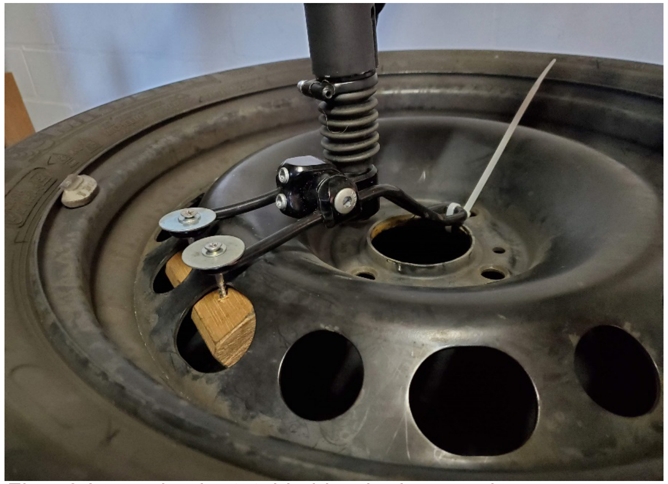

Fig. 72 Improvized rotatable bicycle dummy pin.

Fig. 71 Assembly line station simulation.

Fig. 73 Crates of bicycle bulk materials.

Fig. 74 Height of assembly materials table.

As described in chapter 6.2, two layouts of station 2 are recreated for testing: the current and relocated handlebar rack layout. These layouts are depicted from above in figure 77 and 78. For further clarification on the recreated assembly line situation, figures 75 and 76 display the used assembly locations. In the relocated handlebars rack situation, the supportive desk is removed. The desk is used to mimic the dummy pen holder from the original assembly situation. The dummy pen holder is used to place and pick up the automated screwdriver during action 2.1 and 2.7 in the original situation to have both hands available for opening the handlebars.
In the relocated assembly situation, placing and picking up the automated screwdriver is unnecessary due to the elimination of the open handlebars actions.


Fig. 75 Simulation of current situation.


Fig. 76 Simulation of handlebar rack relocation.

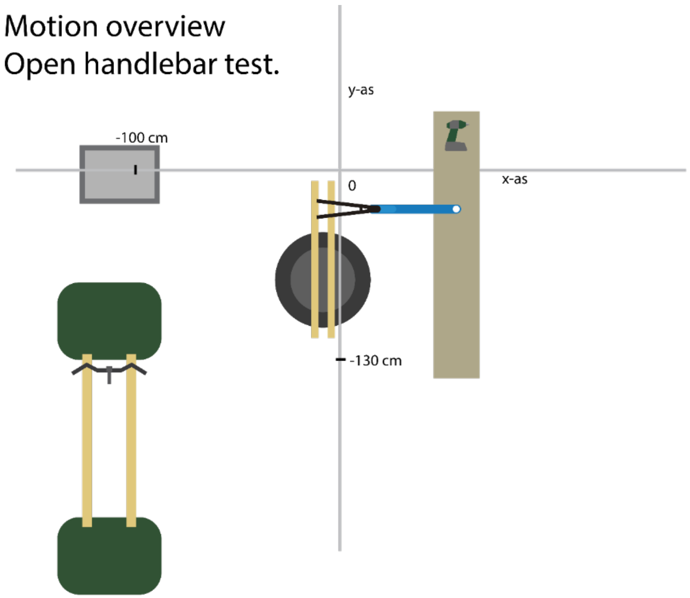

Fig. 77 Simulated open handlebar situation.

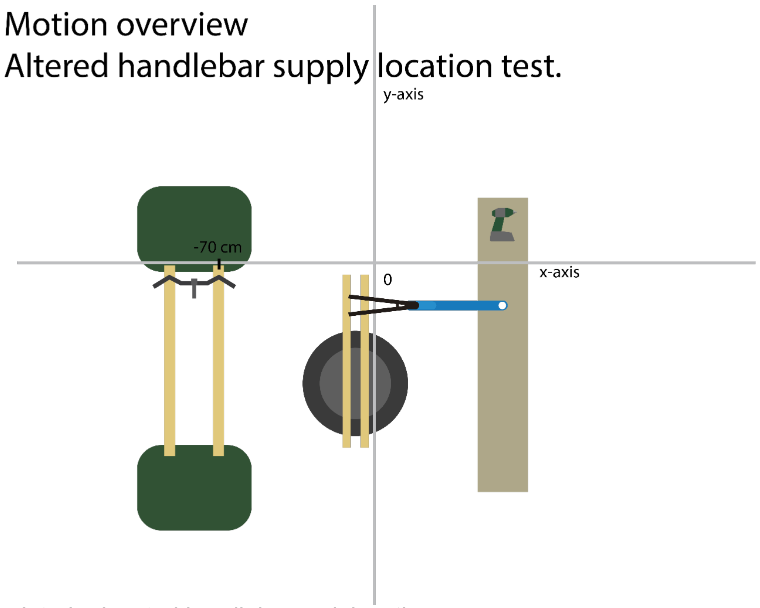

Fig. 78 Simulated relocated handlebar rack location.

The layouts were created using locally available materials. The following material locations were copied from the assembly line video footage for accurate re-enactment of the assembly movements:

- The automated screwdriver
- Bicycle frame holder
- Bicycle frame
- Automated screwdriver resting location
- Handlebars rack
- Handlebars

The location of the materials were determined by measuring the location relative to the assembly location. In figure 79 and 80, the x and y location of the handlebar rack was determined.

Conclusion

The test setup of station 2 was simulated using locally available materials. Using this environment, the assembly operations were captured on video.
In the next chapter, the layout for the second test is described.

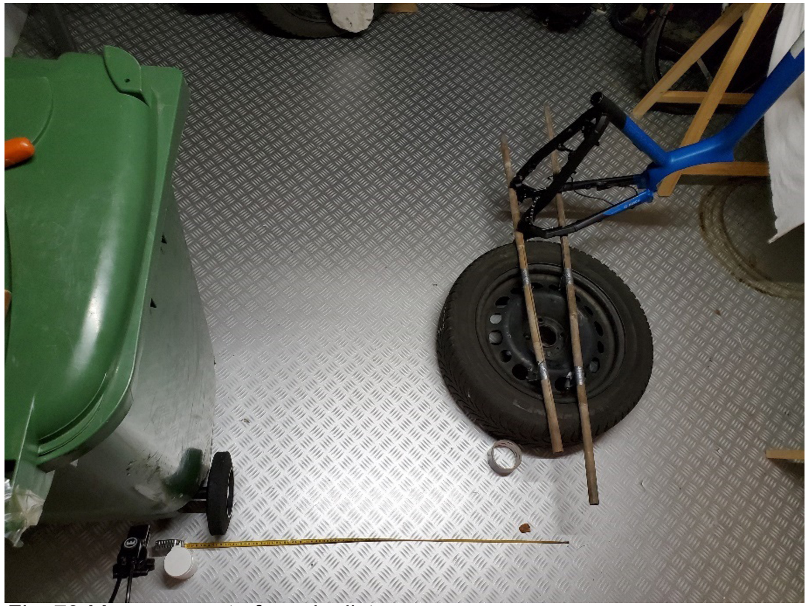

Fig. 79 Measurement of x-axis distance.

Fig. 80 Measurement of y-axis distance.

Two layouts of station 3 were created for testing: The current layout and the relocated bins layout. The goal of the recreated current layout is to create a benchmark to which the reordered layout can be compared. A comparison of the assembly line video footage to the reordered layout would be unfair due to the difference in skill of the assembler and the investigator in performing the specific assembly operation itself. Ideally, the tests would have been performed with assemblers, but due to the covid-19 situation, this has not been possible. To eliminate the differences in assembly skill, the reordered layout is compared to the recreated current layout and the assembly actions are performed by the investigator in both layouts. The layouts are presented in figure 81, 82, 83 and 84.

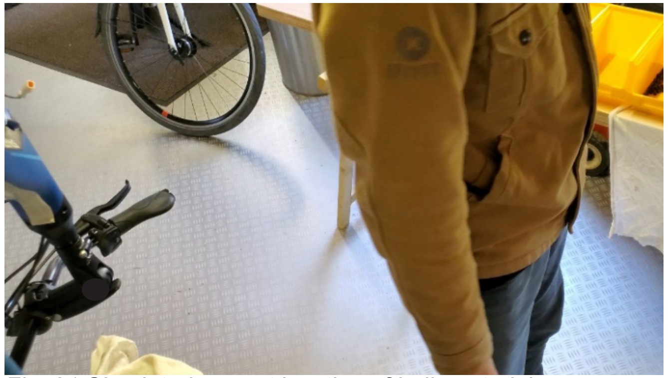

Fig. 81 Simulated current location of bulk materials.

Fig. 82 Relocated bulk materials.

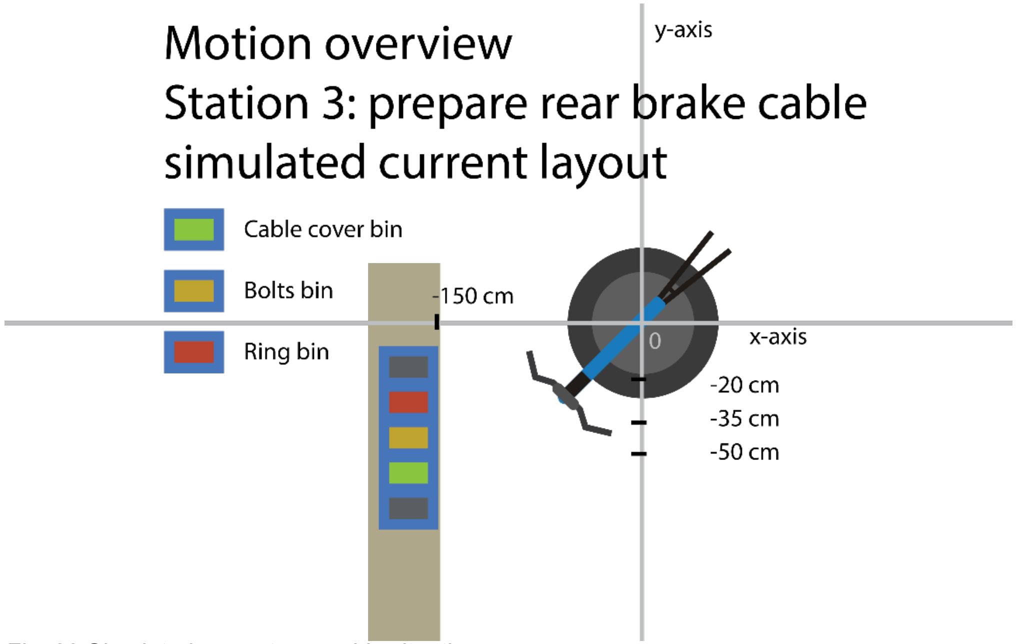

Fig. 83 Simulated current assembly situation.

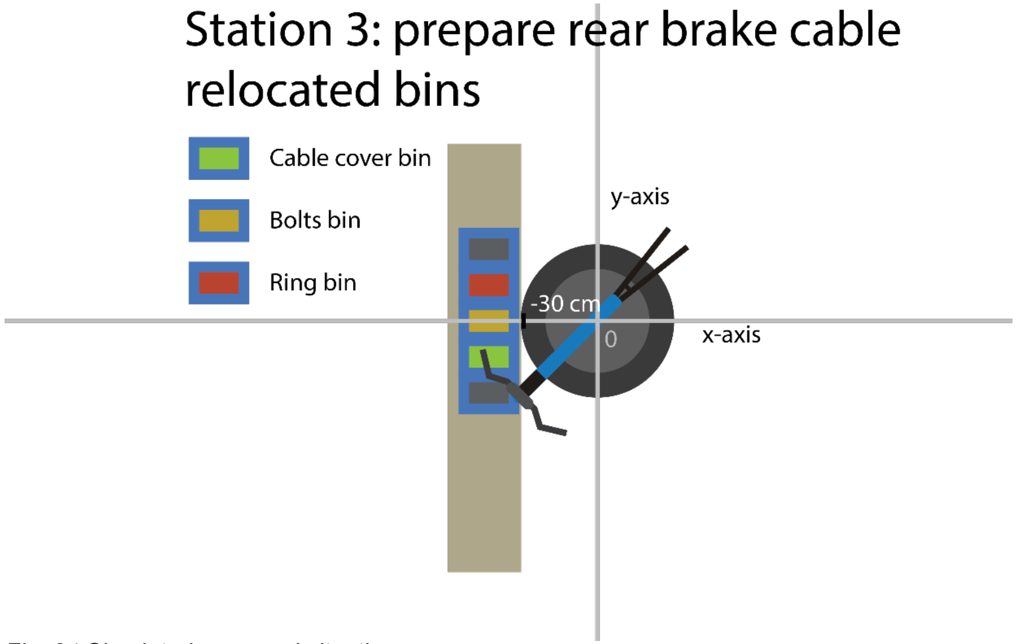

Fig. 84 Simulated proposed situation.

The layouts were created using locally available materials. The following material locations were copied from the assembly line video footage for accurate re-enactment of the assembly movements:

- Assembly table height
- Bicycle frame holder
- Bicycle frame
- Hollow bolt bin
- Hollow bolts bulk
- Ring bin
- Rings bulk
- Cable cover bin
- Cable cover

The rear brakes and cable cover screws which can be seen in figure 85 are also present, but unused during testing. Measuring the distances of the materials to create the proposed setup locations for the setup is displayed in figure 85 and 86.

Conclusion

The assembly line was reconstructed using available materials. To simulate the assembly line situation correctly, the distances of the materials were measured to result in the same required movements for the assembler in the reconstructed situation.

These two layouts were then used to determine the difference in assembly time in the two proposed assembly scenarios. The layout of the third test is described in the next chapter.

Fig. 85 Material location on the x-axis.

Fig. 86 Material location on the y-axis.

For station 5, two assembly layouts were constructed, a reconstruction of the current assembly station and the relocated grease pot layout. The reconstructed station is depicted in figure 87 and 89. The relocated grease pot layout is depicted in figure 88 and 90. The lower table is used to hold the bolt bin, because the height of the bin is lower than the assembly table in the assembly line video footage. The reconstructed assembly line layout also served as benchmark for the performance of the grease pot layout, as described in chapter 6.7.

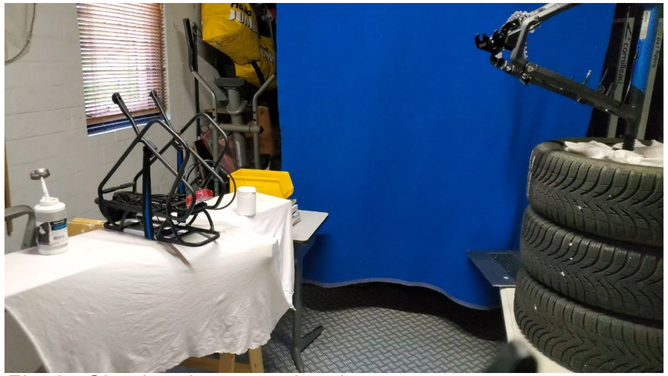

Fig. 87 Simulated current situation.

Fig. 88 Simulated proposed situation.

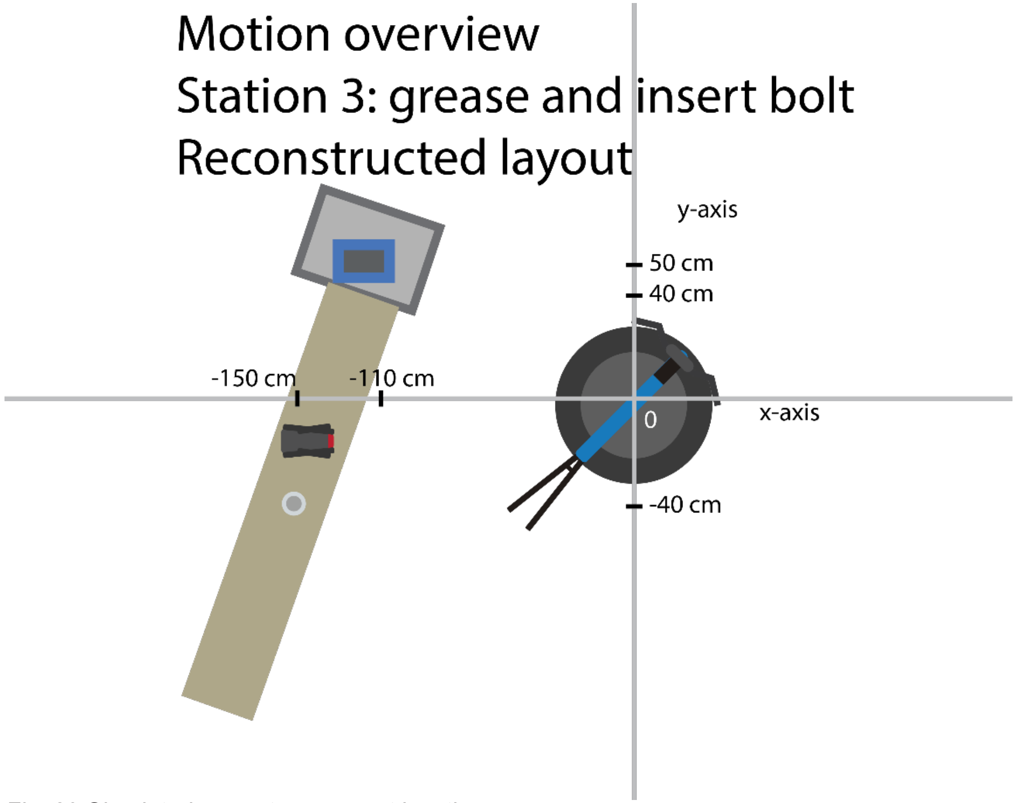

Fig. 89 Simulated current grease pot location.

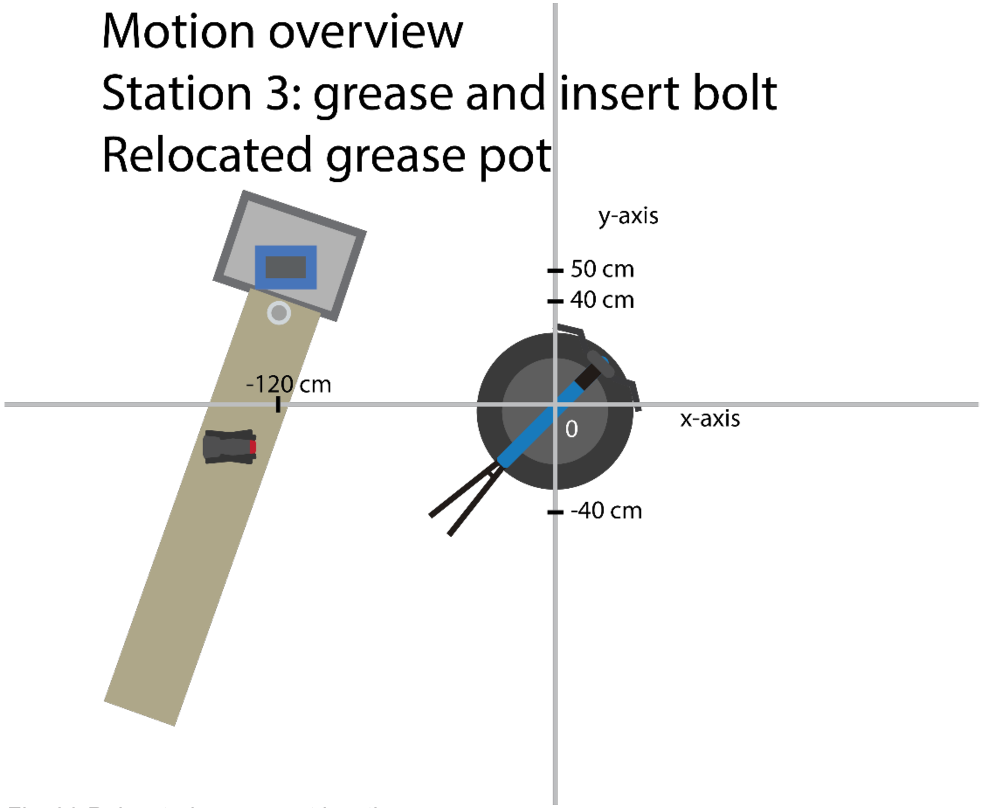

Fig. 90 Relocated grease pot location.

The following material locations were copied from the assembly line video footage for accurate re-enactment of the assembly movements:

- Assembly table height
- Bicycle frame holder
- Bicycle frame
- Grease pot
- Luggage carrier
- Bolt bin
- Bolts bulk

The placement of the materials using a tape measure and a point of reference can be seen in figure 91 and 92.

Conclusion of testing chapter

In this chapter, three tests were performed with two goals in mind: Determining the feasibility and desirability of the proposed assembly line improvements and determining the viability of the implementation of the investigation method. The feasibility and desirability of the proposed assembly line improvements was determined by performing the assembly operations in the rebuild environment of the current situation at the assembly line and the proposed improved situation at the assembly line. The assembly operations were then performed 10x in both situations, and the outcomes were compared.

This comparison was based on the evaluation criteria based on Accell's goals; The assembly time and amount of list of requirement violations were compared. The outcomes of this investigation are described in chapter 7, along with the results of investigations performed in previous chapters.

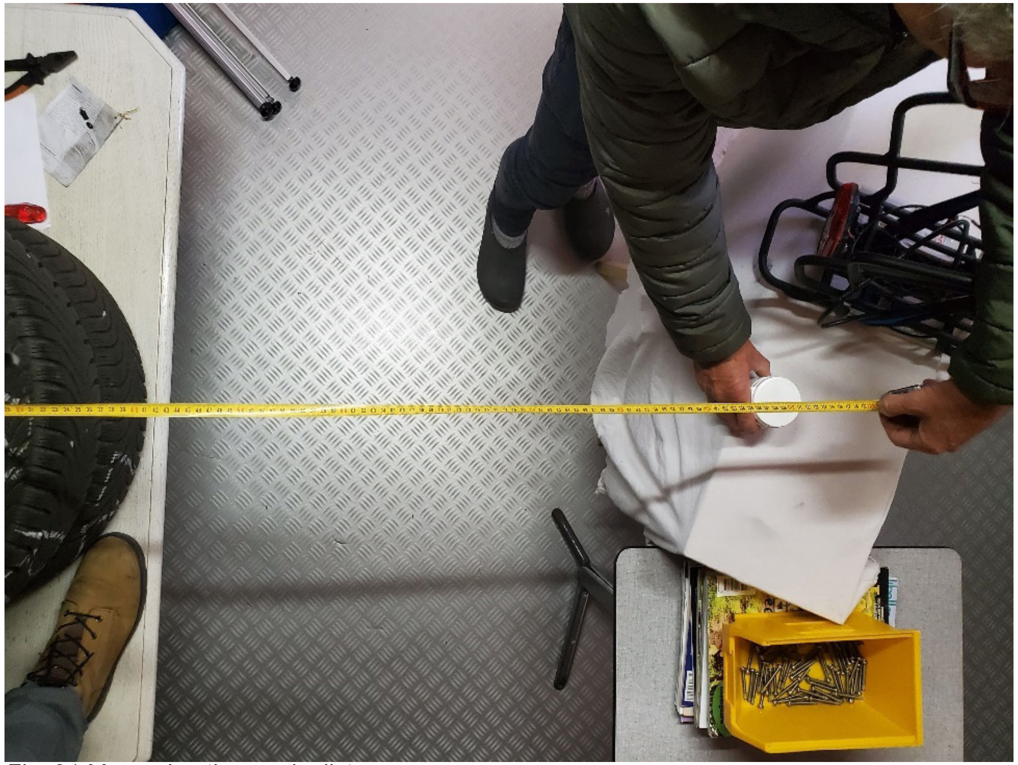

Fig. 91 Measuring the x-axis distance.

Fig. 92 Measuring the y-axis distance.

7. Results

Introduction (1) — Situation (2) — Theory (3) — Ideation (4) — Concept (5) — Testing (6) — **Results (7)** — Conclusion (8) — Discussion (9)

Chapter 7 first describes the results from the current assembly line investigation. Then, the results from the three tests of applying the final method to the situations in station 2,3 and 5 are described. Finally, the chapter displays the three deliverables of the project.

7.1 Assembly line performance

Chapter goal

This chapter details what the current performance of the assembly line is, why the assembly line is at that level of performance and which improvement aspects were found during the investigation. Due to the confidential nature of these results, they are removed from the public version of the report. In the confidential version of the report, the overall assembly line efficiency, the efficiency per assembly station, the time spent per type of action, the possible impact of performing line balancing and the application of BasicMOST to the assembly line are discussed here.

Due to the confidential nature of this chapter's results, they are removed from the public version of the report. In the confidential version of the report, the overall assembly line efficiency, the efficiency per assembly station, the time spent per type of action, the possible impact of performing line balancing and the application of BasicMOST to the assembly line are discussed here.

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7.2. Test outcomes station 2: fastening handlebars

Outcomes of method application to video footage
The method was tested three times as described in chapter 6. Here, the results of the proposed methods are compared.

The actions were performed as planned, the video footage is included in the data package that can be retrieved from the NextCloud of the RoboFiets project. The start and end times of the action sequence were recorded and visualized.

As is described in table 15, the recorded operation at the assembly line took 20 seconds. Over a sample of 10 tests, the open handlebar situation took 13.7 seconds on average. The standard deviation for the test results is σ = 0.95 and the median is 14. These findings are visualised in a box plot on the next page (figure 96).

The operation with open handlebars and changed layout took 6.7 seconds on average. The standard deviation for the test results is σ = 0.92 and the median is 6.5. Providing the handlebars in an open position did not eliminate the movements 2.4 to 2.7 as was expected. Rather, new assembly actions were required to move the handlebars. The second improvement attempt capitalized on this change by

Video footage	Number	End time	Action
Assembly station 2: Current situation	2.1	2	Turn to grab handlebars
	2.2	3	Bend forward for grabbing handlebars
	2.3	4	Lifting handlebars from rack
	2.4	6	Move handlebars to openable orientation
	2.5	13	Open & adjust handlebars
	2.6	15	Turn, grab & orient screwdriver
	2.7	17	Correct bolt orientation on handlebars
	2.8	20	Step over setup to orient handlebars
Assembly station 2: Handlebars open	2.a	1	Grab automated screwdriver.
	2.b	2	Place screwdriver on table.
	2.c	5	Grab handlebars
	2.d	6	Lift handlebars and change hands.
	2.e	8	Grab automated screwdriver.
	2.f	10	Move to assembly location.
	2.g	11	Orient automated screwdriver in handlebars.
	2.h	14	Orient handlebars on bicycle frame.
Assembly station 2: Handlebars open and relocated handlebars supply	2.i	1	Grab screwdriver.
	2.j	2	Turn and reach for handlebars.
	2.k	3	Grab handlebars.
	2.l	4	Orient screwdriver in handlebars.
	2.m	7	Orient handlebars on bicycle frame.

Table. 15 violated requirements of station 2

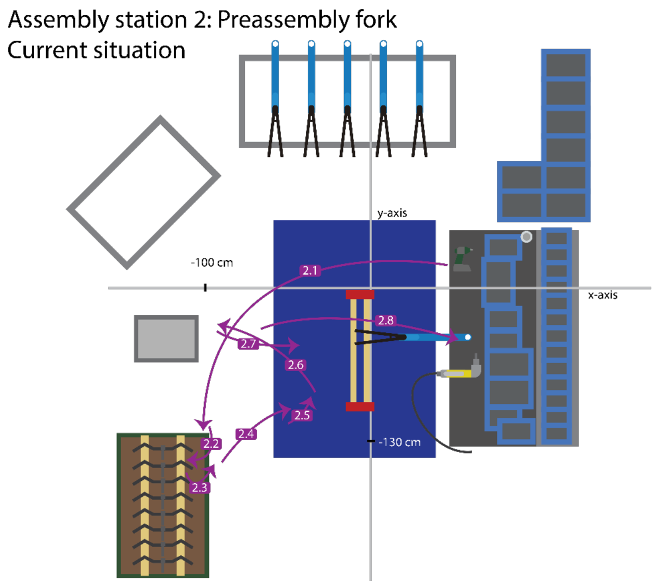

Fig. 93 Currrent assembly movements at station 2.

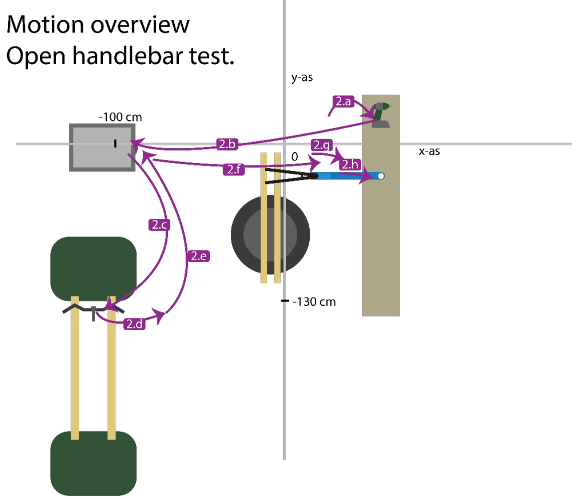

Fig. 94 Movements for open handlebars situation.

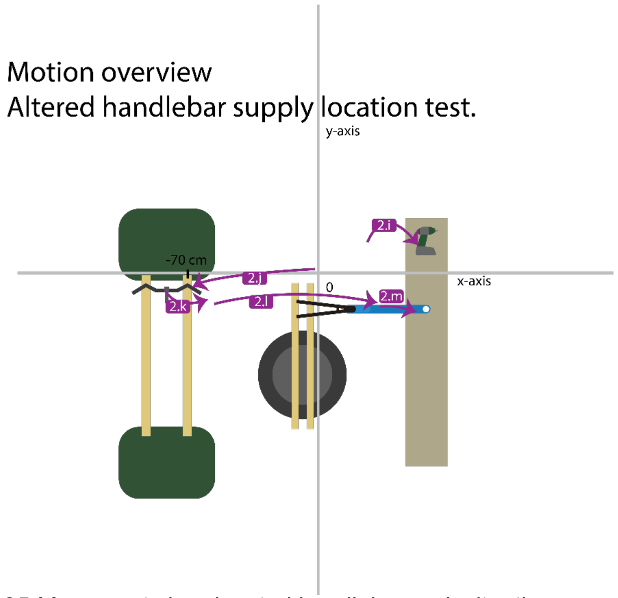

Fig. 95 Movements in relocated handlebar rack situation.

removing the newly found movements which were still required to be performed to move the handlebars. Figure 93, 94 and 95 depict the two layouts and the current assembly line situation.
In table 16, the found amount of requirement violations for the assembly line situation, the handlebars open situation and the handlebars open + relocated handlebars supply are depicted.

Table 15 and 16 show that the assembly time and requirement violations were reduced during test 1 and 2. These findings verify the assumptions A.2, A.4, A.6 and A.8 and refute assumptions A.1, A.3, A.5 and A.7. This provides a first argument for accepting the main research hypotheses, aH1 and bH1. It also provides a first argument for refuting the main null hypotheses, aH0 and bH0. The assumptions per test are depicted below.

Test 1: open handlebars situation
aH0
A.1: Providing the handlebars in open orientation does not influence the time required to perform actions 2.1 to 2.8.
aH1
A.2: Providing the handlebars in open orientation reduces the time required to perform actions 2.1 to 2.8.
bH0
A.3: Providing the handlebars in open orientation does not influence the amount of list of requirement violations during actions 2.1 to 2.8.
bH1
A.4: Providing the handlebars in open orientation reduces the amount of list of requirements violations during actions 2.1 to 2.8.

Test 2: Altered handlebar rack layout
aH0
A.5: Relocating the handlebars rack from x = -100 cm and y = -130 cm to x = - 70 cm does not influence the time required to perform action 2.1 to 2.8.
aH1
A.6: Relocating the handlebars rack from x = -100 cm and y = -130 cm to x = - 70 cm and y = 0 cm reduces the time required to perform action 2.1 to 2.8.
bH0
A.7: Relocating the handlebars rack from x = -100 cm and y = -130 cm to x = - 70 cm and y = 0 cm does not influence the amount of list of requirement violations during actions 2.1 to 2.8.
bH1
A.8: Relocating the handlebars rack from x = -100 cm and y = -130 cm to x = - 70 cm and y = 0 cm reduces the amount of list of requirement violations during actions 2.1 to 2.8.

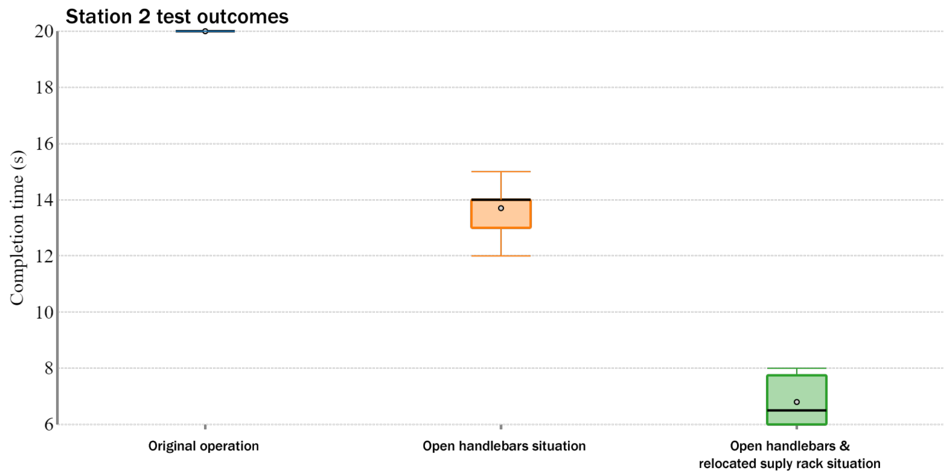

Fig. 96 Boxplot overview of assembly times per test.

	Violated efficiency requirements	Violated workload requirements	Total requirements violations
Station 2: Assembly line video footage	8	18	26
Station 2: Handlebars open	0	8	8
Station 2: Handlebars open and relocated handlebars supply	0	4	4

Table. 16 Violated requirements for station 2

7.3 Test outcomes station 3: preparing rear brake cable

Adding the cable cover, a hollow bolt and a ring to the rear brake cable takes 9.0 seconds in the current situation over 5 assembly operations, see table 17.

The layout of the current situation can be seen in figure 97. During this operation, the assembler is required to turn and reach for materials as can be seen in table 17. The situation is simulated to compare the assembly time of the professional assembler to the investigator's assembly speed.
The simulated layout, figure 98, uses a table for the placement of the bins.

During testing, five actions were performed which took 10.8 seconds on average over 10 tests. This means that the investigator performs the assembly operations one second slower compared to the assembly line video. The standard deviation for the test results is $\sigma = 1.13$ and the median is 10.5.

The material bins were placed at 30 cm distance from the bicycle frame instead of the 150 cm used in the tested changed layout (figure 99). This reduces the travel distance of the assembler. The assembly operation required three actions which took 7.0 seconds on average to perform.

Video footage	Number	End time	Action
Assembly line video	3.1	1	Turn towards frame
	3.2	3	Turn and reach for cable cover
	3.3	4	Slide cable cover over break cable
	3.4	8	Turn and reach for ring and hollow bolt
	3.5	9	Slide hollow bolt and ring over break cable
Reconstructed assembly situation	3.a	1	Grab cable cover.
	3.b	4	Place cable cover over cable.
	3.c	5	Grab hollow bolt.
	3.d	7	Grab ring.
	3.e	11	Place hollow bolt and ring on cable.
Close layout	3.f	1	Grab cable cover and ring.
	3.g	2	Grab hollow bolt.
	3.h	7	Place cable cover, ring and hollow bolt on cable.

Table. 17 violated requirements of station 3

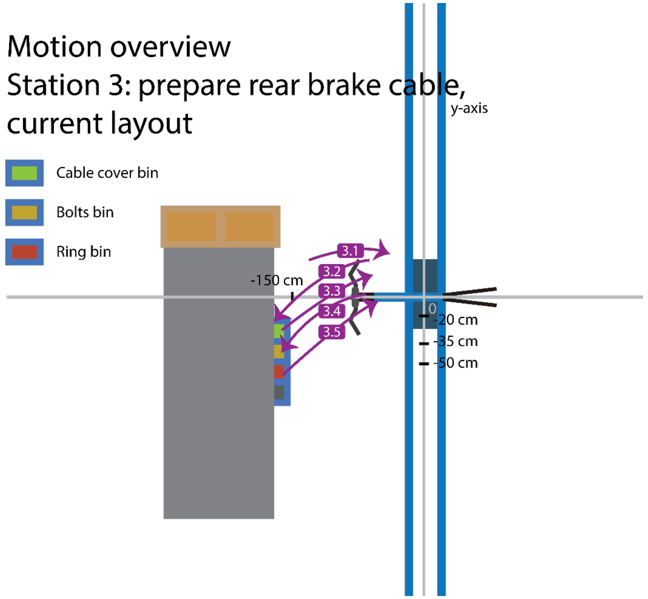

Fig. 97 Current required movements at the assembly line .

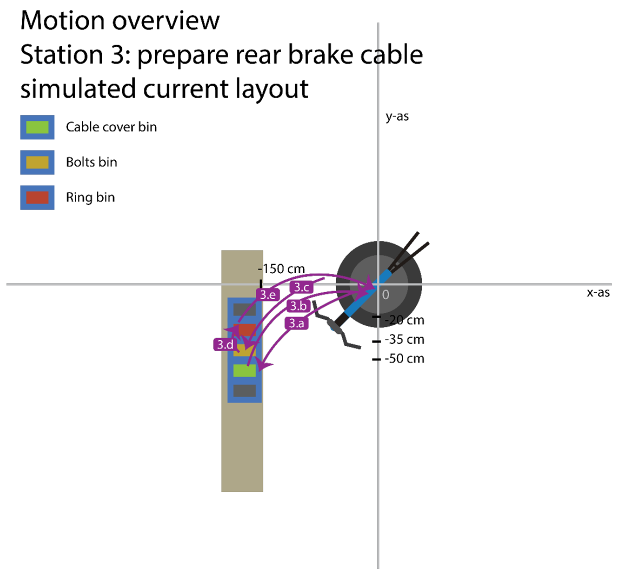

Fig. 98 Overview of observed movements in the altered layout.

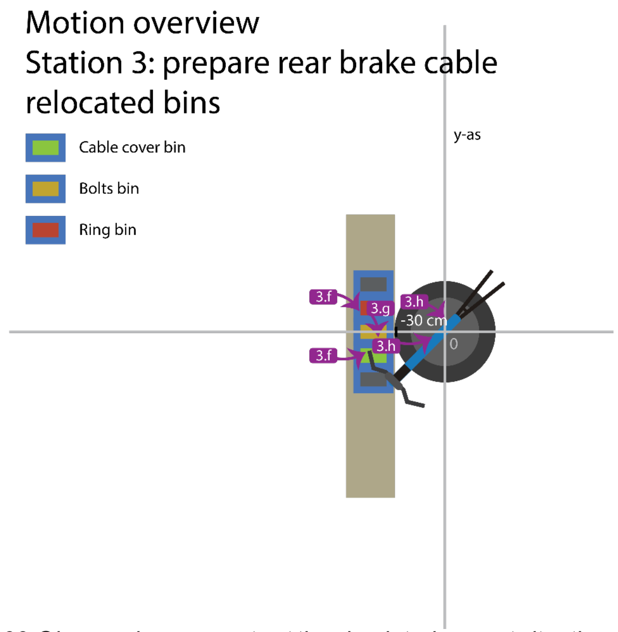

Fig. 99 Observed movements at the simulated current situation.

The standard deviation for the test results is σ = 0.94 and the median is 7. The outcomes are visualised with a box plot in figure 100.

In this layout, it was possible to use both hands to grab the cable and ring simultaneously, therefore both are included in action 3.f.

From the data in table 17 and 18, we find that the assembly time difference between the reconstructed and close layout is 4 seconds and the amount of requirement violations is reduced by 7.

These findings verify the assumptions A.10 and A.12. The assumptions A.9 and A.11 are refuted by these findings.

This provides a second argument for accepting the main research hypotheses, aH1 and bH1. It also provides a second argument for refuting the main null hypotheses, aH0 and bH0.

The time required to perform the 10 tests are depicted in figure 100.

The assumptions for the tests are described below.

aH0
A.9: Relocating the material bins from x = -150 cm and y = -20/-35/-50 cm to x = -30 cm and y = 22.5/7.5/-75 cm does not influence the time required to perform action 3.1 to 3.5.
aH1
A.10: Relocating the material bins from x = -150 cm and y = -20/-35/-50 cm to x = -30 cm and y = 22.5/7.5/-75 cm reduces the time required to perform action 3.1 to 3.5.
bH0
A.11: Relocating the material bins from x = -150 cm and y = -20/-35/-50 cm to x = -30 cm and y = 22.5/7.5/-75 cm does not influence the amount of list of requirement violations during actions 3.1 to 3.5.
bH1
A.12: Relocating the material bins from x = -150 cm and y = -20/-35/-50 cm to x = -30 cm and y = 22.5/7.5/-75 cm reduces the amount of list of requirement violations during actions 3.1 to 3.5.

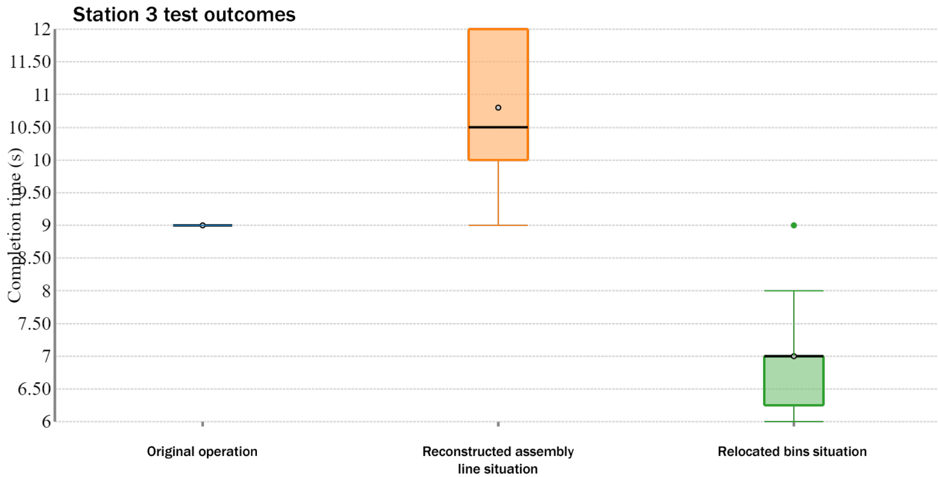

Fig. 100 Boxplot overview of assembly times per test.

	Violated efficiency requirements	Violated workload requirements	Total requirements violations
Station 3: Assembly line video footage	0	7	7
Station 3: Reconstructed assembly situation	0	7	7
Station 3: Relocated bins	0	0	0

Table. 18 Violated requirements for station 3

7.4 Test outcomes station 5: Grease and position bolt on luggage carrier

The original, recorded operation at the assembly line took 5 seconds to perform. The operation in the reconstructed layout situation took 5.5 seconds on average over 10 tests. The operation in the relocated grease pot situation took 4.4 seconds on average over 10 tests. The standard deviation for these test results is σ = 0.53 and the median is 5.5. The overview of the assembly times per test is presented in table 19. A box plot of the test results is provided in figure 104 on the next page.

The reconstructed assembly situation required more assembly time than the assembly line video. A reason for this difference could be the experience of the assembler. The reduction of assembly time between he reconstructed situation and the relocated grease pot was 1.1 seconds. The standard deviation for these test results is σ = 0.69 and the median is 4.

The assembly operations are displayed in figure 101, 102 and 103.
An interesting find is that the location of the grease pot allowed the assembler to lift the luggage carrier from the right.
This causes the bolt and the luggage carrier to align faster since only 90 degrees of turning are required compared to the 270 degrees required in the current

Video footage	Number	End time	Action
Assembly line video	5.1	1	Turn to grab bolt
	5.2	1	Grab bolt
	5.3	3	Reach to grease bolt
	5.4	5	Turn to orient bolt in luggage carrier
Reconstructed assembly situation			
	5.a	1	Grab bolt after turning.
	5.b	3	Grease bolt.
	5.c	4	Lift luggage carrier.
	5.d	6	Push bolt in luggage carrier.
Relocated grease pot			
	5.e	1	Grab bolt after turning.
	5.f	1	Grease bolt.
	5.g	2	Lift luggage carrier.
	5.h	4	Push bolt in luggage carrier.

Table. 19 violated requirements of station 3

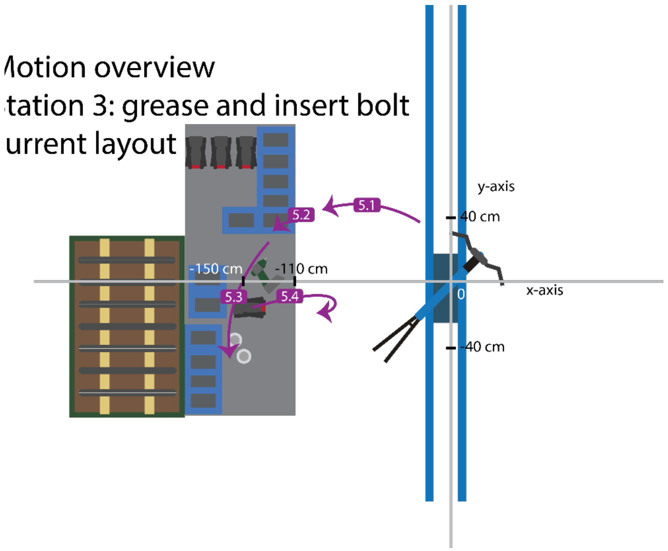

Fig. 101 Motions at current assembly station.

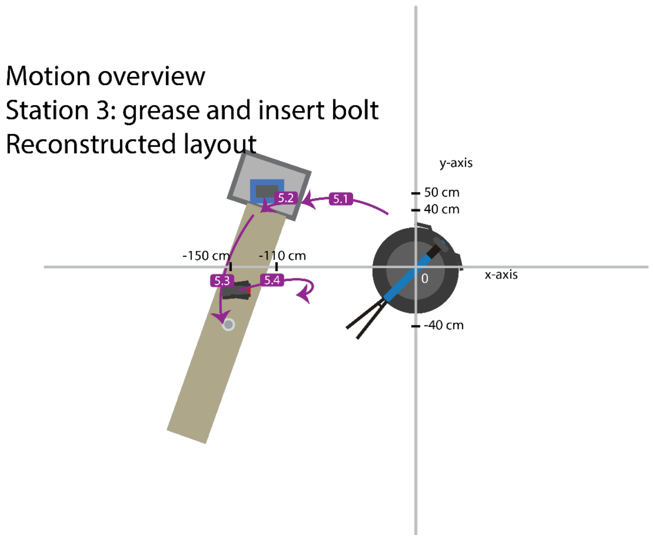

Fig. 102 Motions in recunstructed assembly station.

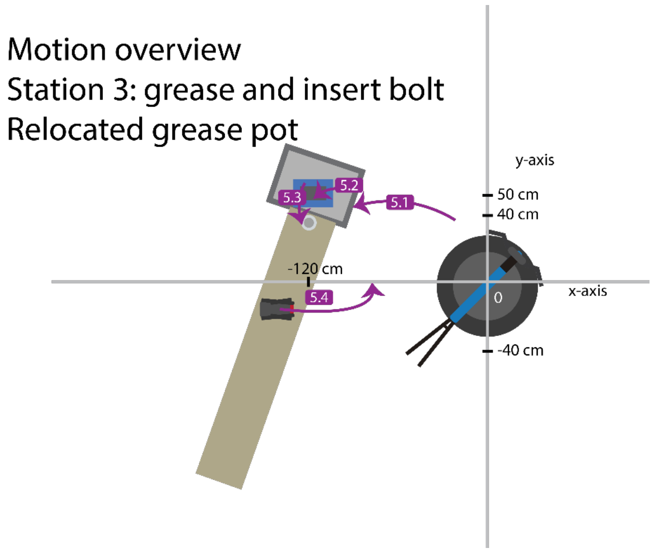

Fig. 103 Motions at proposed assembly station.

assembly line situation.

The relocation of the grease pot reduced the requirement violations from 6 to 4. The type of requirements varies between the reconstructed assembly situation and the assembly line video footage due to slight movement variations between the assembler and the investigator due to body size difference.

From the data in table 19 and 20 and the box plot in figure 104, we find that the assembly time between the reconstructed and close layout is reduced by 1.1 seconds and the amount of requirement violations is reduced by 2.

These findings verify the assumptions A.14 and A.16. The assumptions A.13 and A.15 are refuted by these findings. This provides a third argument for accepting the main research hypotheses, aH1 and bH1. It also provides a third argument for refuting the main null hypotheses, aH0 and bH0.

Test 4: Relocating the grease pot
aH0
A.13: Relocating the grease pot from x = -150 cm and y = -40 cm to x = - 120 cm and y = 40 cm does not influence the time required to perform action 5.1 to 5.4.
aH1
A.14: Relocating the grease pot from x = -150 cm and y = -40 cm to x = - 120 cm and y = 40 cm reduces the time required to perform action 5.1 to 5.4.
bH0
A.15: Relocating the grease pot from x = -150 cm and y = -40 cm to x = - 120 cm and y = 40 cm does not influence the amount of list of requirement violations during actions 5.1 to 5.4.
bH1
A.16: Relocating the grease pot from x = -150 cm and y = -40 cm to x = - 120 cm and y = 40 cm reduces the amount of list of requirement violations during actions 5.1 to 5.4.

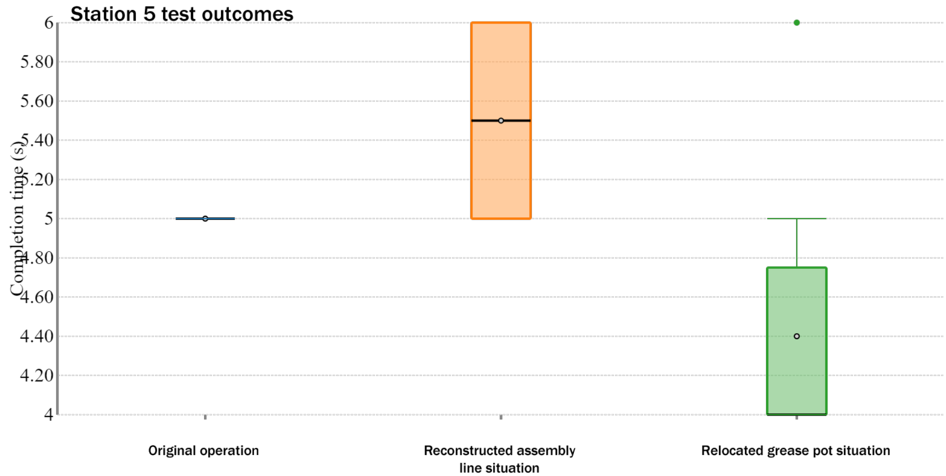

Fig. 104 A boxplot overview of the assembly times from the tests.

	Violated efficiency requirements	Violated workload requirements	Total requirements violations
Station 5: Assembly line video footage	3	3	6
Station 5: Reconstructed assembly situation	1	5	6
Station 5: Relocated grease pot	1	3	4

Table. 20 Violated requirements for station 5

8. Conclusion

In this chapter, the conclusions on the four test outcomes (station 2, station 3 and station 5) are presented. The meaning of the outcomes to Accell's goals and the main research hypotheses are also detailed here.

8.1 Presented deliverables

This project aimed to deliver three materials. These deliverables were presented throughout the project and can be found in the previous chapters.

1. A reusable method which allows the investigator to determine the largest assembly time reduction opportunities and structurally generate improvements.

This method was described in chapter 5 Concept and applied in chapter 6 Testing to the ABC Model assembly situation to demonstrate its applicability. The solutions found by the application of the method were tested according to chapter 6 and the outcomes of the tests are depicted in chapter 7 Results. The method is thereby proven to be reusable because it was used for the definition of the improvement proposals.

2. An overview of the ABC Model assembly line detailing the improvement opportunities.

The ideated improvements can be found in 6.1, and the tested improvements for the largest time reduction opportunities are described in detail in chapter 6. This overview can thus be used for further research on this assembly line.

3. A multitude of ideated and tested improvements for the largest time reduction opportunities.

This overview is depicted in figure 105. Accell and the RoboFiets project can use this overview to start further investigations for the improvement of the assembly line situation.

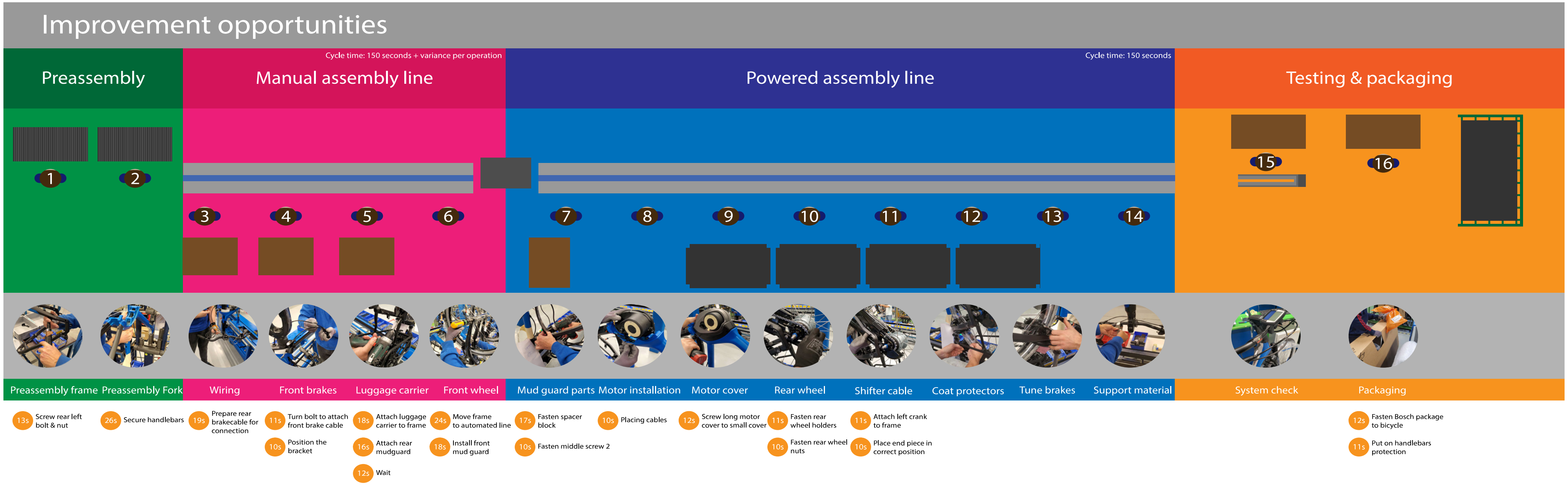

Fig. 105 Deliverable 2: overview of improvement opportunities.

8.2 Findings

Chapter goal
This chapter describes the most important findings of this research.

Automation not yet implementable
Due to a large bicycle variety it would be costly to implement automation possiblities in the current situation as a large variety of models requires an automation solution that is able to deal with the differences between these models.
Next to that there is a large part variety currently used at the assembly line. This is no problem for humans but would be a very costly expense to make an automation solution to deal with these varieties.
The last reason why automation is not yet possible is the design of the bicycle itself. The current design of the bicycle is not optimized for assembly. The result is that the assemblers have to manage working around other parts of the bicycle to reach the assembly locations. Again, this is not a problem for humans, but would be a problem for an automation solution.
These findings make the implementation of automation not yet feasible in the current situation, but could be implemented in a later stage.

Design for assembly could improve assembly
As was found in the context analysis, the bicycles are not optimized for assembly. This has to do with three main factors:

1. The parts that are used for the bicycle are not standardized. This variety of parts increases the variety of assembly operation types, which causes the assembly line to facilitate various assembly operations at the same location.
2. The bicycle frame suppliers use broader tolerances than specified by Accell. This leads to differences of 1 mm per bicycle frame pipe. In total, this can lead to a difference of 4 mm of assembly location over the whole length of a bicycle. For human assembly, this is not an issue. For automated assembly, the solution would require ways to adept to the varying assembly locations.
3. The design department doesn't prioritize design for assembly. The focus is more on safety and beauty. This results in a more complicated assembly situation for the assembler.

Both of the above mentioned points could be improved by the design department taking design for assembly into account. The suspicion is that this would be the best investment the company could do to reduce bicycle assembly time, but further research on this suspicion is needed to come to a sound conclusion.

Currently no backtracking of damages at assembly line
Currently damages are tracked by using stickers. These stickers don't indicate what kind of damage is found. The bicyle with the sticker is completely finished and then send to the repair department where it is disassembled or repaired.
If the sitckers could indicate where the damage to the bicycle originates from, the root causes could be found and solved. Thereby would it save time to take the damaged bicycle out of the assembly line when damage is found, so no time and energy is spent on assembling the bicycle and disassembling it.

Improvement of communication
The context analysis also showed limited communication between different departments. The example of the paint department and the fitting of holes was given. Improving this communication could potentially structurally improve the assembly line. A more in depth analysis of the communication situation is needed to make sound conclusions on this.

Bicycle assembly is 47% efficient, room for improvement.
In the current state of the assembly line, it is 47% efficient. As showed in this report, this gives a lot of room for improvements. The Covid-19 situation made the testing set-up of the tests more about small improvements that could be done without too many additional costs. The results have shown that these improvements can be made and are useful.
By using the proposed method for all assembly situation could potentially increase efficiency without the extensive additional costs.

Simple, low cost solutions can be found using the method
As stated above, the test set-ups and tests show that low cost solutions can be found, using the proposed method. The low cost improvements can be made on three aspects:

1. Material location

The material location of the assemblage materials were changed during testing. As shown in the test, by changing the locations of the assembly materials, potential time could be saved, by making it easier for the assembler to perform actions.

2. Layout of the assembly station

Closely related to material location is the assembly station lay out. By changing the lay out, in x, y, or z axis, the assembly situation could be made so that the assembler needs to perform less actions like, squatting, turning around and reaching

3. Communication for fast improvements

As stated above and shown in the test of station 2, improving the communication between the different departments of the assembly line could improve different situations significantly by filtering the non-value added actions that are caused by a lack of knowledge in other departments.

These three aspects don't require additional costs for the company to implement them. Further investigation of the possiblities of the current situation could be useful to find the low hanging fruit.

Line balancing can be useful after reduction non-value-added work
Line balancing seemd the first solution to increase assembly line efficiency, as we have shown in chapter 7, line balancing would have the most effect when most of the non-value-added work is reduced. When this is done, line balancing could potentially decrease the time that is needed for the assembly of the bicycle and improve workers conditions at the same time.

Assembly personnel can use expertise to improve assembly line
As tried in the ideation of this project and found by the context analysis, the expertise of the assembler could be used to improve the assembly line. Because the assembler know the assemblage process and have hands-on experience, that expertise could potentially improve possible solution. This needs to be tested and requires a change at mangerial level.

This concludes the chapter on the findings of this project. In the following chapters we will ellaborate on the other findings: The conclusion of the tests (chapter 8.3) and the conclusion on the applied methods for the violation of requirements (chapter 8.4).

8.3 Conclusion effectiveness of applied methods for assembly time reduction

Accell's goals for this project were to improve the efficiency, bicycle quality, assembly costs, assembler workload and faulty bicycles amount of their assembly lines. To structurally improve these various aspects of the assembly line, a sequence of methods was created. This sequence of methods was used to investigate the ABC Model assembly line to test the validity of the proposed methods. The outcome of this investigation were three tested assembly situations which reduced average assembly time, depicted in table 21.

As depicted in table 22, the assumptions based on the main null hypothesis aH0:"The application of the proposed methods does not affect assembly time." are refuted. The reduction of average assembly time due to the application of the methods at all four tests leads to the rejection of the main null hypothesis

This reduction also verified the assumptions based on the main research hypothesis aH1: "The application of the proposed methods causes assembly time reduction." The verified assumptions indicate that the application of the methods to assembly lines can cause assembly time reduction. To accept this hypothesis, however, more research is required on the application of improvement categories beyond layout changes and a larger amount of testing data is required.
The reduction of assembly time was not the only desired improvement. To facilitate the improvement of bicycle quality, assembly costs, physical assembler workload and faulty bicycle amount, the characteristics of these subjects are detailed in the list of requirements. This enables the investigator to find different assembly line aspects which can be improved.

Operation	ABC Model video footage Assembly time (s)	Reconstructed test environment Assembly time (s)	Altered test environment Assembly time (s)
Station 2: orient handlebars on frame	20	13.7 (Open handlebar orientation)	6.7
Station 3: prepare rear brake cable	9	10.8	7.0
Station 5: grease and insert bolt	5	5.5	4.4

Table. 21 Changes in assembly time

	aH0	aH1	bH0	bH1
Test 1	Assumption A.1 (refuted)	Assumption A.2 (verified)	Assumption A.3 (refuted)	Assumption A.4 (verified)
Test 2	Assumption A.5 (refuted)	Assumption A.6 (verified)	Assumption A.7 (refuted)	Assumption A.8 (verified)
Test 3	Assumption A.9 (refuted)	Assumption A.10 (verified)	Assumption A.11 (refuted)	Assumption A.12 (verified)
Test 4	Assumption A.13 (refuted)	Assumption A.14 (verified)	Assumption A.15 (refuted)	Assumption A.16 (verified)

Table. 22 Assumptions verification and refution

8.4 Conclusion on applied methods for requirement violation reduction

Accell's project goals were converted into a list of requirements to measure the state of an assembly operation on the previously mentioned topics. An ideal assembly situation would have no violated requirements. By comparing the assembly line footage to the test footage, we find that the proposed layout changes reduce the number of violated requirements in all four tests, see table 23. The application of the investigation methods lowered the violated workload requirements at all three assembly stations. The slight variation in efficiency/workload violations between station 5's assembly line video footage and the reconstructed assembly situation is due to slightly different movements caused by differences in assembler length, causing the requirement R2.4 being violated instead of R1.6.

Since the violated workload requirements are lowered at station 2 and 3, the application of the methods to the situation allow the assembler to perform work with less workload and produce the same results. In these stations, the workload reduction was mainly due to the removal of taking steps and turning due to the layout changes.

Based on the reduction of violated requirements at all four tests, the assumptions based on bH0: "The application of the proposed methods does not reduce the amount of list of requirement violations." are refuted, as is indicated in table 23. The reduction of violated requirements at all four tests therefore leads to the rejection of bH0.

This violated requirements reduction also validates the assumptions based on hypothesis bH1, "Research hypothesis bH1: "The application of the proposed methods reduces the amount of list of requirement violations", as indicated in table 23. Like research hypothesis aH1, the verified assumptions indicate that the application of the methods to assembly lines can cause reduction of requirement violations. To accept this hypothesis, however, more research is required on the application of improvement categories beyond layout changes and a larger amount of testing data is required.

As mentioned above, the application of the method sequence leads to an improvement of the assembly line situation. While the focus was on the time reduction, this time reduction was also checked with the improvements for the other requirements. The outcome is that the focus on time reduction also lead to a reduction of violations. This method can thus be used to improve assembly line situations from a multi-aspect view.

	Violated efficiency requirements	Violated workload requirements	Total requirements violations
Station 2: Assembly line video footage	8	18	26
Station 2: Handlebars open	0	8	8
Station 2: Handlebars open and relocated handlebars supply	0	4	4
Station 3: Assembly line video footage	0	7	7
Station 3: Reconstructed assembly situation	0	7	7
Station 3: Relocated bins	0	0	0
Station 5: Assembly line video footage	2	4	6
Station 5: Reconstructed assembly situation	1	5	6
Station 5: Relocated grease pot	1	3	4

Table. 23 The reduced violations of requirements of the tested stations

This project aimed to provide a method which could be used to repeatedly improve assembly line situations. This method was set up and its capabilities were tested. The implementation of the method at Accell's ABC Model assembly line was used to decrease assembly time and work towards Accell's five goals:

- Increasing efficiency
- Increasing bicycle quality
- Reducing cost
- Reducing assembler workload
- Reducing faulty bicycle amount

This chapter elaborates on the possibilities for future research, possible improvements to the methods and contemplation on what could have been done better during the investigation.

9.1 Discussion of project

Value added time, inefficient at station 4 & 5
When the assembly line footage was divided into value-added work and non-value-added work, two stations contained a large amount of value-added time. The operation "Turn bolt to attach front brake cable: at station 4 contains 44 seconds of value-added time. This is above the normal amount of value-added time. Upon closer inspection, this operation requires manual fastening of a bolt with a wrench, which takes 44 seconds. Although this time consists of value-added time, it is clearly an inefficient way of fastening the bolt. At station 8, the operation "Placing cables" is performed. Placing these cables requires 16 seconds of value-added time. Again, upon closer inspection, the placement of the cables in the frame is an inefficient time-consuming activity. Although this assembly time is considered value-adding, the operation is not efficient. For a future iteration of the investigation method, the assembly operations with the largest amount of value-added can be investigated to find out if these value-adding movements themselves are efficient.

Testing other solution categories
The performed tests involved changing the layout of the assembly stations. The capabilities of the methods towards other categories of improvement such as bicycle design and interdepartmental communication remain untested at this moment due the Covid-19 situation. To create an applicable method, these aspects of collaboration and teamwork are yet to be implemented.

Impact on other bicycle models
To determine the validity of the impact of layout changes, further investigation regarding the effects on other bicycle models must be performed to know if the found solutions do not slow down or make assembly operations for other bicycles impossible.

Improvement of methods
Multiple steps can be taken to improve the proposed methods. In practice, the categorisation of the root causes was not as guiding as expected, since the root cause itself provided ample direction. The video analysis method could be simplified to reduce the time required for the analysis of an assembly line situation. For this, further investigation of the MOST method must be conducted. Especially to take a look into why the time as identified by MOST, differed from the time found in the video. Possible reasons could be the different age, other assembly situations in another country or outdated data.
The list of requirements can be further investigated to be clearer and simpler. This could make the method easier to implement.

Benchmark test 1 and 2
Currently, test 1 has no reconstructed benchmark test to which to compare the assembly operations to besides the assembly line video footage. To provide a more complete dataset, the situation with a closed handlebar can be tested by recreating the assembly line layout.

Recommended further investigation
At Accell, to reduce the current assembly time and investigate the effects of the methods in other situations, further investigation of the methods should be performed.
To use practical experience to improve the assembly lines, testing of the methods would ideally involve the assemblers in the ideation phase. Also, the participation of the assemblers to the testing would provide more accurate results, since the assemblers are the people who have to work in the proposed situation. To cover the other aspects of assembly line improvement, testing the other aspects such as bicycle design and interdepartmental communication, other testing must be performed to conclude on these aspects.

Additional insight on low cost solutions
As shown by the test setup, low cost solutions can be found by moving material location and changing the assembly station layout. Due to the limited capacity of the test space, the distribution of the materials in the new situation was not tested. This could also not be tested in the company itself, because of the Covid-19 situation. When one wants to implement these proposed improvements, it would be recommended to also do a test on the distribution. If the distribution takes longer due to the new lay out and location, the possible time improvements and costs reduction could be less than is predicted in this report. Testing and calculating the results could give a conclusion on this issue.

This concludes the discussion chapter. As shown above improving an assembly line is a multifaceted project that could potentially have time reduction results.

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Nextcloud data package

Front fork, frame, luggage carrier videos	*Nextcloud*
Video files of assembly line work at station 6 & 8	*Nextcloud*
Testing videos	*Nextcloud*

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IDE Master Graduation

Project team, Procedural checks and personal Project brief

This document contains the agreements made between student and supervisory team about the student's IDE Master Graduation Project. This document can also include the involvement of an external organisation, however, it does not cover any legal employment relationship that the student and the client (might) agree upon. Next to that, this document facilitates the required procedural checks. In this document:

- The student defines the team, what he/she is going to do/deliver and how that will come about.
- SSC E&SA (Shared Service Center, Education & Student Affairs) reports on the student's registration and study progress.
- IDE's Board of Examiners confirms if the student is allowed to start the Graduation Project.

USE ADOBE ACROBAT READER TO OPEN, EDIT AND SAVE THIS DOCUMENT

Download again and reopen in case you tried other software, such as Preview (Mac) or a webbrowser.

STUDENT DATA & MASTER PROGRAMME

Save this form according the format "IDE Master Graduation Project Brief_familyname_firstname_studentnumber_dd-mm-yyyy".
Complete all blue parts of the form and include the approved Project Brief in your Graduation Report as Appendix 1 !

family name: Bosman

initials: FWA given name: Fabian

student number:

street & no.:

zipcode & city:

country:

phone:

email:

Your master programme (only select the options that apply to you):

IDE master(s): [x] IPD [ ] DfI [ ] SPD

2nd non-IDE master:

individual programme: - - (give date of approval)

honours programme: [ ] Honours Programme Master

specialisation / annotation: [ ] Medisign [ ] Tech. in Sustainable Design [ ] Entrepeneurship

SUPERVISORY TEAM **

Fill in the required data for the supervisory team members. Please check the instructions on the right !

** chair: Doris Aschenbrenner dept. / section: Design Engineering

** mentor: Bas Flipsen dept. / section: Design Engineering

2nd mentor:

organisation:

city: country:

comments (optional)

Chair should request the IDE Board of Examiners for approval of a non-IDE mentor, including a motivation letter and c.v..

Second mentor only applies in case the assignment is hosted by an external organisation.

Ensure a heterogeneous team. In case you wish to include two team members from the same section, please explain why.

TU Delft

APPROVAL PROJECT BRIEF

To be filled in by the chair of the supervisory team.

chair ______________ date - - ______ signature ______________

CHECK STUDY PROGRESS

To be filled in by the SSC E&SA (Shared Service Center, Education & Student Affairs), after approval of the project brief by the Chair. The study progress will be checked for a 2nd time just before the green light meeting.

Master electives no. of EC accumulated in total: ______ EC

Of which, taking the conditional requirements into account, can be part of the exam programme ______ EC

List of electives obtained before the third semester without approval of the BoE ______

YES all 1st year master courses passed

NO missing 1st year master courses are:

name ______________ date - - ______ signature ______________

FORMAL APPROVAL GRADUATION PROJECT

To be filled in by the Board of Examiners of IDE TU Delft. Please check the supervisory team and study the parts of the brief marked **. Next, please assess, (dis)approve and sign this Project Brief, by using the criteria below.

- Does the project fit within the (MSc)-programme of the student (taking into account, if described, the activities done next to the obligatory MSc specific courses)?
- Is the level of the project challenging enough for a MSc IDE graduating student?
- Is the project expected to be doable within 100 working days/20 weeks ?
- Does the composition of the supervisory team comply with the regulations and fit the assignment ?

Content: APPROVED NOT APPROVED

Procedure: APPROVED NOT APPROVED

comments

name ______________ date - - ______ signature ______________

Partially automating a cargo bicycle assembly line

project title

Please state the title of your graduation project (above) and the start date and end date (below). Keep the title compact and simple. Do not use abbreviations. The remainder of this document allows you to define and clarify your graduation project.

start date 07 - 10 - 2019

20 - 03 - 2020 end date

INTRODUCTION **

Please describe, the context of your project, and address the main stakeholders (interests) within this context in a concise yet complete manner. Who are involved, what do they value and how do they currently operate within the given context? What are the main opportunities and limitations you are currently aware of (cultural- and social norms, resources (time, money,...), technology, ...).

The bicycle production company Accell wants to bring their production facilities back to the Netherlands. Together with TU Delft they plan to initiate the RoboFiets project which explores the implementation of new technology on bicycle production and assembly. The return of production is enabled by introducing batch size 1 production so that individualized bicycles can be produced.

Traditionally, bicycle assembly has been a manual task. This is due to the intricate component shapes, complex movements during assembly and the variety of bicycle models and components.

Accell currently uses two production methods for bicycle assembly: standardized bicycle assembly using assembly lines and custom bicycle assembly using one worker per bicycle. The RoboFiets project includes enabling Accell to produce customized bicycles using assembly lines including human-robot co-production.

The manual assembly can be improved using robotic manipulators to automate assembly steps as well as increasing the effectiveness of the current workforce. The resulting opportunities for Accell include selling customized bicycles directly to customers, reducing bicycle stock and lowering worker strain while reducing production time and costs.

Therefore, Accell wants to identify the automation potential for their new personalized cargo bicycle assembly line and determine which automation methods can be applied. As a sub-part of the RoboFiets project, this graduation project aims to automate a step in Accell's new cargo bicycle assembly line.

Stakeholders and values
The RoboFiets project main stakeholders are Accell, their employees and the TU Delft.
Accell's relevant values for this project are enabling full bicycle customization, reducing production costs, reducing employee strain and keeping their production methods secret. The values of the Accell employees are unknown and will be investigated during the project. The TU Delft values the creation of knowledge related to robotics and assembly automation.

Main limitations
- A 100-day time constraint
- Technical difficulty of implementing automation solutions
- Acceptance of automation solutions from Accell employees
- Proving technical feasibility of assembly automation
- Investment cost limit related to bicycle sales volume

space available for images / figures on next page

introduction (continued): space for images

image / figure 1: Assembly steps currently involve manual labor.

image / figure 2: The assembly process is partially automated in the future.

PROBLEM DEFINITION **

Limit and define the scope and solution space of your project to one that is manageable within one Master Graduation Project of 30 EC (= 20 full time weeks or 100 working days) and clearly indicate what issue(s) should be addressed in this project.

Accell wants to automate their cargo bicycle assembly line to enable customized bicycle production. Therefore, this projects problem can be defined as: It is currently unknown how Accell's cargo bicycle assembly line tasks can be automated using robotics.

Examples of automation opportunities are: frame painting, logo placement, handle bar assembly, spokes placement, tire fastening and the general assembly of other components such as the handlebars, pedals, fork, brakes, chain mechanism, cargo box assembly and cargo box placement.

The project will start with an overview of automation opportunities and will be narrowed down to produce a proof of concept of one specific automation solution.

Challenges

The current main challenges for this project include:
- Finding which automation is possible per step
- Dealing with component complexity of one bicycle type
- Dealing with complexity of movements during assembly
- Gaining acceptance of solutions by personnel

ASSIGNMENT **

State in 2 or 3 sentences what you are going to research, design, create and / or generate, that will solve (part of) the issue(s) pointed out in "problem definition". Then illustrate this assignment by indicating what kind of solution you expect and / or aim to deliver, for instance: a product, a product-service combination, a strategy illustrated through product or product-service combination ideas, ... In case of a Specialisation and/or Annotation, make sure the assignment reflects this/these.

"Design automation solutions for one or more assembly steps for the Accell cargo bicycle assembly line."

In order to adhere to this general project assignment, my vision of what must be the result of this project is: Provide a proof of concept for one automated step of the Accell cargo bicycle assembly line.

This vision includes developing the technology to a level which can test the prototype in a realistic setting (TRL level 5/6)

I envision the solution space for this assignment to include the implementation of robotics, supporting personnel by making assembly steps easier and more comfortable, implementation of automation methods from other industries and designs of custom automation methods.

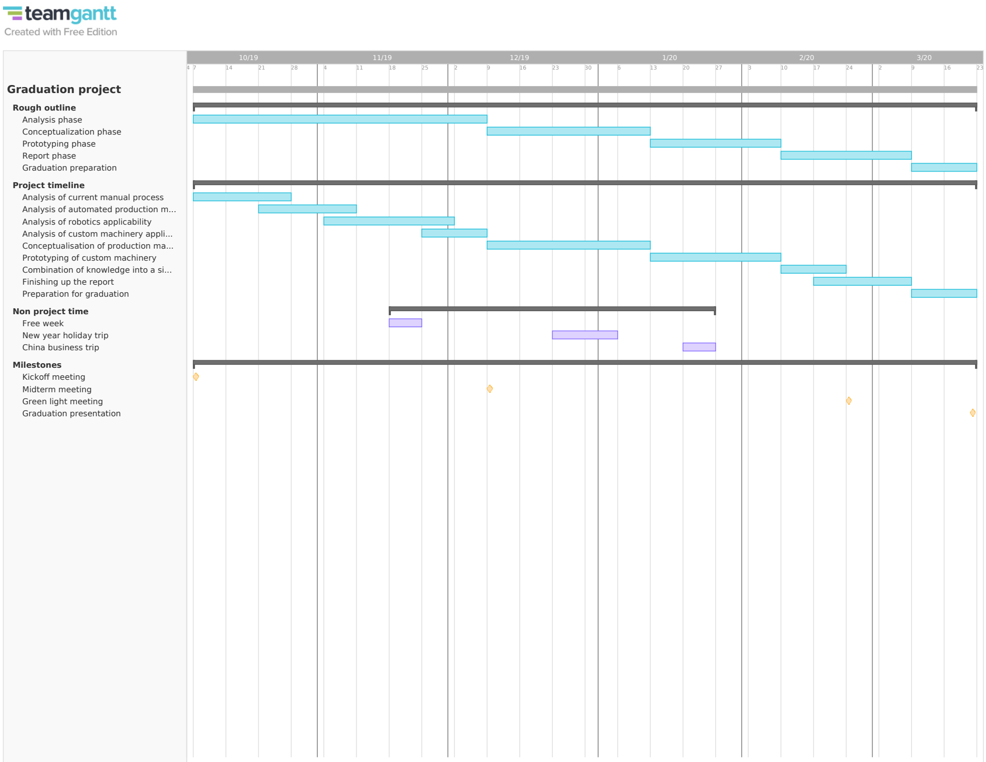
Deliverables

- A framework classifying suitability for automation per assembly step.
- Automation concepts for multiple assembly steps.
- A proof of concept prototype of an automated assembly step.
- A report detailing automation possibilities of the assembly line.

PLANNING AND APPROACH **

Include a Gantt Chart (replace the example below - more examples can be found in Manual 2) that shows the different phases of your project, deliverables you have in mind, meetings, and how you plan to spend your time. Please note that all activities should fit within the given net time of 30 EC = 20 full time weeks or 100 working days, and your planning should include a kick-off meeting, mid-term meeting, green light meeting and graduation ceremony. Illustrate your Gantt Chart by, for instance, explaining your approach, and please indicate periods of part-time activities and/or periods of not spending time on your graduation project, if any, for instance because of holidays or parallel activities.

start date 7 - 10 - 2019 | 20 - 3 - 2020 end date



For the production of a framework classifying suitability for automation per assembly step, I plan to investigate the assembly line by working there for two to three weeks, taking existing literature into account.

In order to generate automation concepts for assembly steps, I plan to analyze automation methods from other industries by performing literature review and watching "How it's made" videos. Further automation research would include analysis of robotics capabilities by performing literature review, investigation of a cargo bicycle at SAM XL, cooperating with Robohouse on robotics knowlege and participating in a robotics course at SAM XL. To create a prototype of an automated assembly step, I plan to design and build a custom machinery application using the design process learned at TU Delft.

Furthermore, the production methods from Accel's customized production methods will be analyzed to investigate the possibilities of implementation of customization in the assembly line.

Time off
During the project I plan to take 1 week of vacation after the midterm meeting, two weeks vacation during New Year and one week for a business trip to China, which still has an undetermined date.

MOTIVATION AND PERSONAL AMBITIONS

Explain why you set up this project, what competences you want to prove and learn. For example: acquired competences from your MSc programme, the elective semester, extra-curricular activities (etc.) and point out the competences you have yet developed. Optionally, describe which personal learning ambitions you explicitly want to address in this project, on top of the learning objectives of the Graduation Project, such as: in depth knowledge a on specific subject, broadening your competences or experimenting with a specific tool and/or methodology, ... Stick to no more than five ambitions.

Motivation
The RoboFiets assignment is an opportunity to support a company while learning more on the topics which personally interest me such as production techniques, production automation and designing for production. Conveniently, these subjects are also key aspects of product design.

Competences
During the MSc program, I improved my skills related to prototyping, conceptualizing practical solutions and implementing user needs. During the elective semester, an internship abroad allowed me to experience the design process from idea to production run. I started to understand which product aspects are relevant when preparing for mass production and assembly.

Ambitions
I would like to increase production in the Netherlands. In order to achieve this, I plan to start a company which produces low cost production machinery to allow tinkerers, maker spaces and other companies to perform production themselves, instead of shipping these responsibilities abroad.

Risk management
The general RoboFiets project aims to explore a wide variety of opportunities relating to the production of bicycles. The amount of possibilities could cause the graduation project to lose focus. This risk can be mitigated by clearly defining the scope of the project and maintaining vigilance.

FINAL COMMENTS

In case your project brief needs final comments, please add any information you think is relevant.

DESIGN FOR our future

TUDelft

3653

IDE Master Graduation

Project team, Procedural checks and personal Project brief

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family name: Bosman
initials: FWA given name: Fabian
student number: [redacted]
street & no.
zipcode & city
country
phone
email

Your master programme (only select the options that apply to you):
IDE master(s): ★ IPD ◯ DfI ◯ SPD
2nd non-IDE master:
individual programme: - - (give date of approval)
honours programme: ◯ Honours Programme Master
specialisation / annotation: ◯ Medisign ◯ Tech. in Sustainable Design ◯ Entrepeneurship

SUPERVISORY TEAM **

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** chair: Doris Aschenbrenner dept. / section: Design Engineering MMC
** mentor: Bas Flipsen dept. / section: Design Engineering IDFS
2nd mentor:
organisation:
city: country:

comments (optional)

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Ensure a heterogeneous team. In case you wish to include two team members from the same section, please explain why.

Procedural Checks - IDE Master Graduation

TU Delft

APPROVAL PROJECT BRIEF
To be filled in by the chair of the supervisory team.

chair Doris Aschenbrenner date 1 - 10 - 2019 signature

CHECK STUDY PROGRESS
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Of which, taking the conditional requirements into account, can be part of the exam programme 30 EC

List of electives obtained before the third semester without approval of the BoE

(X) YES all 1st year master courses passed

( ) NO missing 1st year master courses are:

name date 8-10-2019 signature CB

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Content: (V) APPROVED ( ) NOT APPROVED

Procedure: (V) APPROVED ( ) NOT APPROVED

- please complete sections in future (now already done by Board of Ex.)

comments

name MJ Magen date 15 - 10 - 19 signature

Initials & Name FWA Bosman Student number 4342712

Title of Project Partially automating a cargo bicycle assembly line

Appendix D, Sub-assembly investigation

Front fork sub-assembly investigation

Introduction
The parts of the front fork do not restrict each other's movements during assembly and can be assembled in different orders. This allows for multiple solutions using simple movements. The specific steps can be seen in the Front fork assembly video.

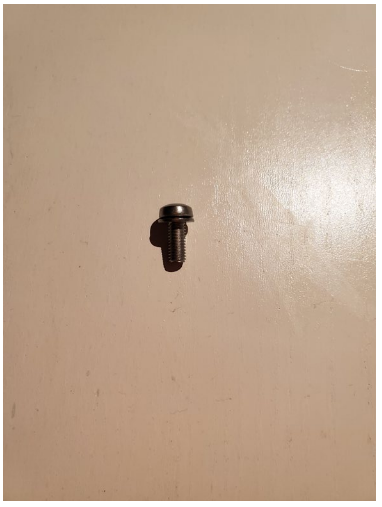
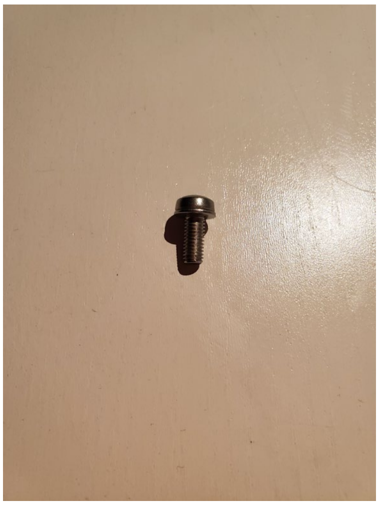
Goal
The goal is to understand how the front fork subassembly can best be assembled taking using linear material placement and fastening using bolts.

Method
The method to reach this goal consists of playing around with the materials and reassembling the subassembly multiple times to understand how the parts interact. Afterwards, an assembly order is chosen which has the least collision of materials.

Placement order

If the automation system does not need to hold parts while assembling others, it can be made simpler. The placement order which allows all parts to be placed and completed without having to wait for another part to be assembled is as follows:

Object	Fastened to	Required movement	
Front fork	-	Linear	
Front mudguard gripping plastic	Front mudguard	Linear	
Front mudguard bracket	Front mudguard gripping plastic	Linear + rotation	

Front mudguard	-	Linear	
Front mudguard bracket washer-integrated bolt left	Front fork + Front mudguard bracket	Linear + rotation	
Front mudguard bracket washer-integrated bolt right	Front fork + Front mudguard bracket	Linear + rotation	

Front light	-	Linear	
Front light washer-integrated bolt	Front fork + Front mudguard + Front light	Linear + rotation	
Front wheel	Front fork	Linear	

Front wheel washer left	Front wheel	Linear	
Front wheel nut left	Front fork + Front wheel washer left + Front wheel	Linear + rotation	
Front wheel washer right	Front wheel	Linear	

Front wheel nut right	Front fork + Front wheel washer right + Front wheel	Linear + rotation	
Front brakes washer left	Front fork	Linear	
Front brakes washer right	Front fork	Linear	

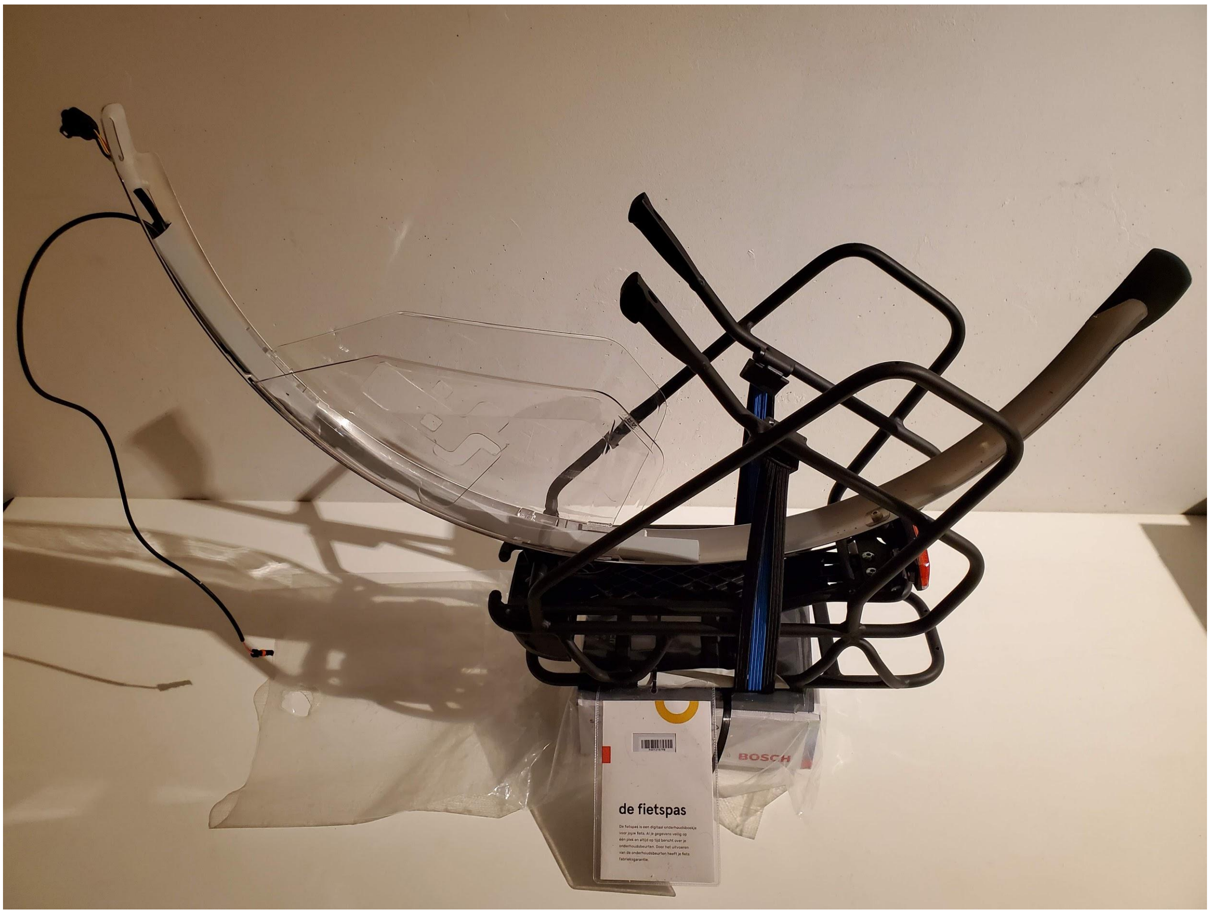
Front brakes bracket	Front fork + Front brakes washer left + Front brakes washer right	Linear	
Front brakes bolt left	Front fork + Front brakes washer left + Front brakes washer right + Front brakes bracket + Front brakes	Linear + rotation	
Front brakes	Front fork + Front brakes washer left + Front brakes washer right + Front brakes bracket	Linear (x6), rotation	

Front brakes bolt right	Front fork + Front brakes washer left + Front brakes washer right + Front brakes bracket + Front brakes	Linear + rotation	
Front wheel box spacer left	Front fork + Front wheel washer left + Front wheel + Front wheel nut left	Linear	
Front wheel box spacer right	Front fork + Front wheel washer left + Front wheel + Front wheel nut right	Linear	

Conclusion

As can be seen in the front fork video (Nextcloud repository data package), the front fork sub-assembly can be assembled using simple linear movements and rotations. The part which will probably cause the most problems are the front brakes because their form is complex and require multi-directional movements to be fastened. Attaching the sub-assembly to the frame requires three operations: Connecting the front light cable, reconnecting the brakes to the brake cable and placing the fork in the allocated frame hole

Luggage carrier sub-assembly



Introduction
Currently the luggage carrier is prepared manually before arriving at the assembly line. Currently, the subassembly does not include the rear mud guard, cable guidance, user supply package and coat protectors. These materials are easier to add in this situation compared to the situation where the luggage carrier is already attached to the bicycle frame.

Goal
The goal is to understand how the luggage carrier fork subassembly can best be assembled taking using linear material placement and fastening using bolts.

Method
The method to reach this goal consists of playing around with the materials and reassembling the subassembly multiple times to understand how the parts interact. Afterwards, an assembly order is chosen which has the least collision of materials.

Results

During assembly and disassembly of the luggage carrier, multiple assembly problems were found:

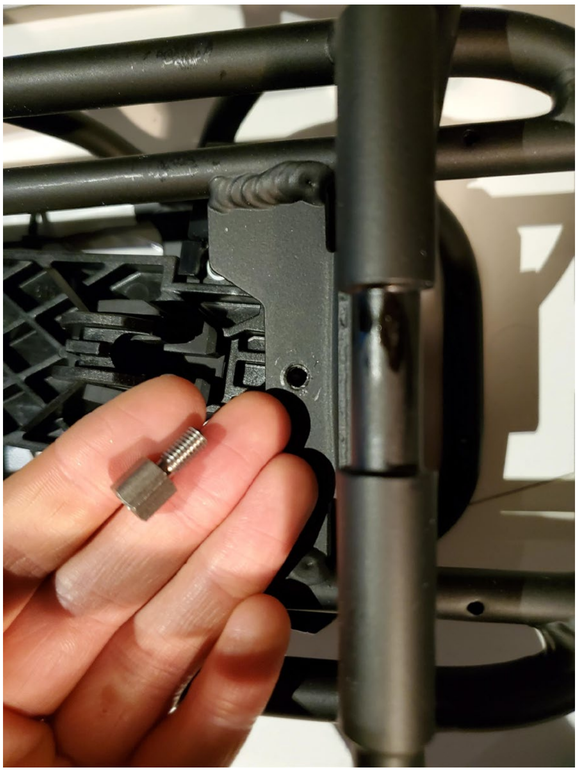
The parts of the luggage carrier restrict each other's movements during assembly such as the battery support screws and the rear light screws needing to be attached before the rear mudguard is installed. The wires, wire guiding plate, coat protectors and lashing straps are flexible. Except for the lashing straps, they require complex, guiding movements to be placed. Furthermore, the wire guiding plate is also hard to guide along the wires even for a human. The enclosure for the wires is also hard to place for humans. The fastening block between the luggage carrier and mudguard is currently not usable for assembly and requires an extra rubber part which the assembly line personnel came up with to avoid having a wiggling rear mud guard. The rings used for fastening the back part of the mudguard and the luggage carrier are also hard to attach. The wires and user materials are attached using tie wraps.

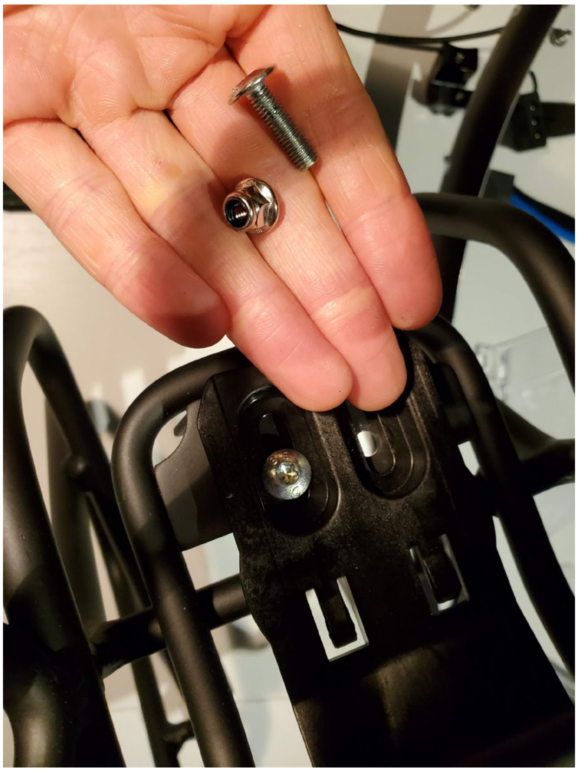
Conclusion

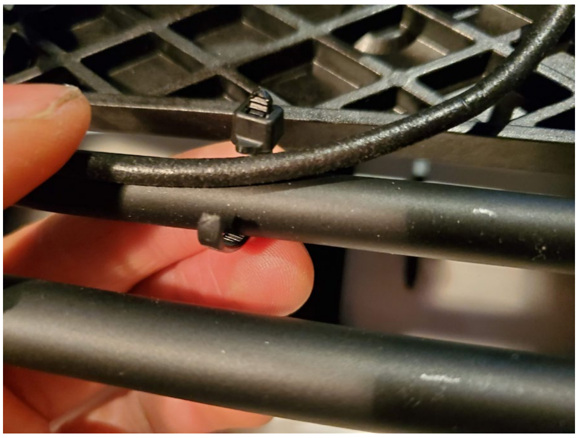
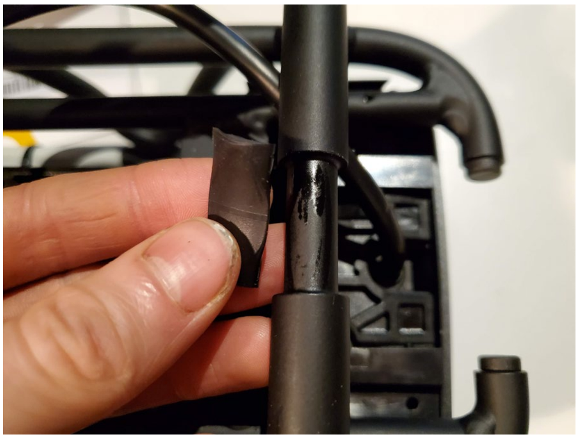
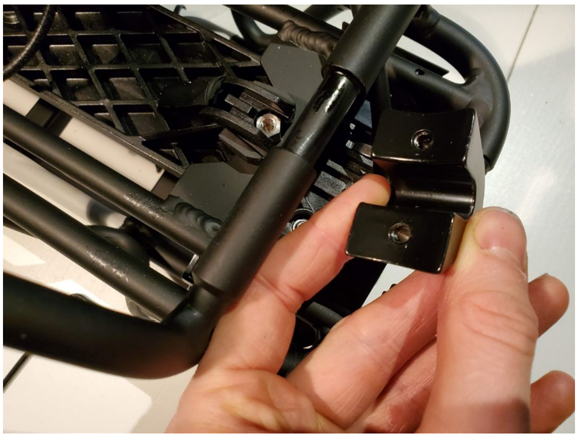
From playing around with the material and reassembling the parts was concluded that this subassembly is not the right starting point for the automation process. The materials used require complex movements, are excessive or restrict the assembly order. Since these parts are hard to assemble for both men (from experience at the assembly line and conversation with employees) and robot (see examples below), it is recommended to first redesign this subassembly to allow for easy assembly before looking into assembly methods.

Images detailing how the luggage carrier is disassembled:

Part	Fastened to	Image

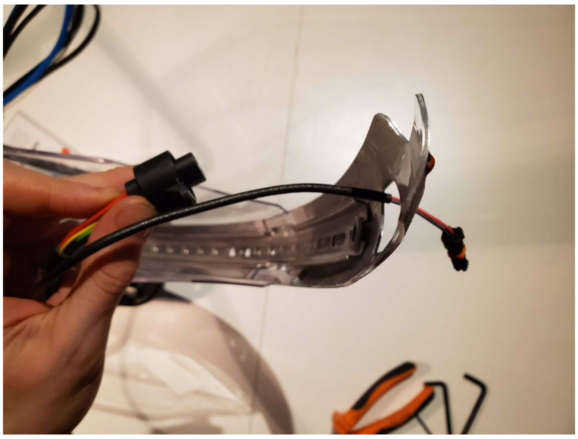
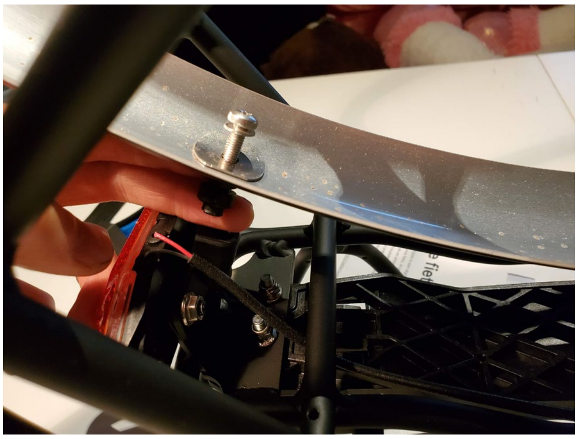
Battery bracket pin	Luggage carrier bracket	
Left battery bracket bolt & nut	Luggage carrier + battery bracket	

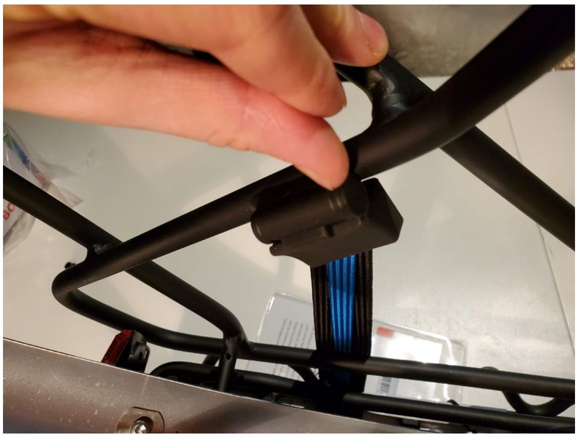
Right battery bracket bolt & nut	Luggage carrier + battery bracket	
Rear light bracket + right rear light nut	Luggage carrier frame	
Left rear light nut	Luggage carrier frame & rear light	

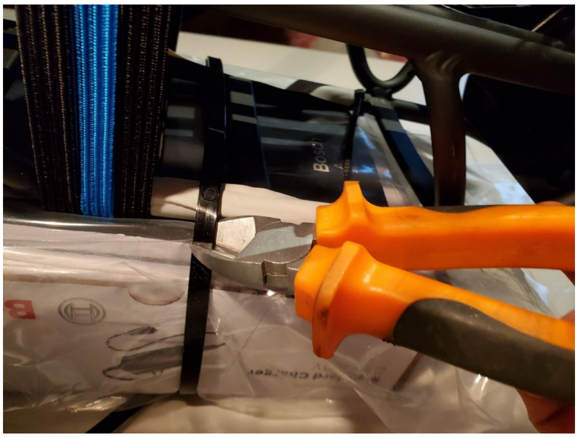
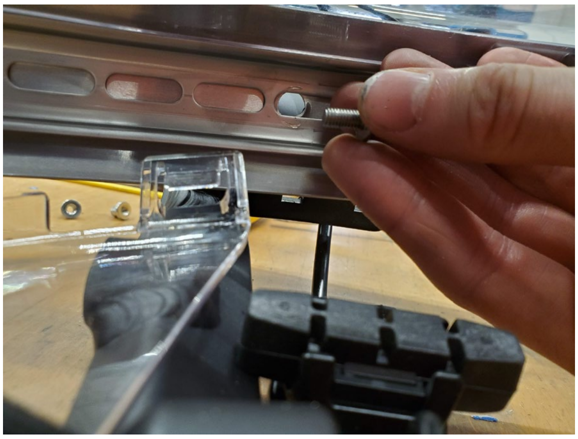
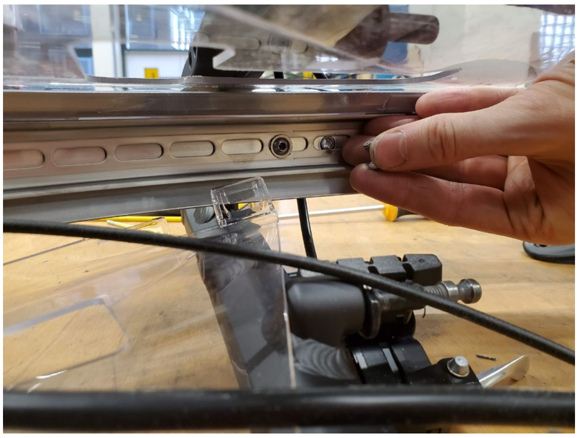
Tie-wrap	Rear light cable	
Spacer rubber	Luggage carrier	
Fastening block	Luggage carrier	
Cable clip	Rear light and battery cable	

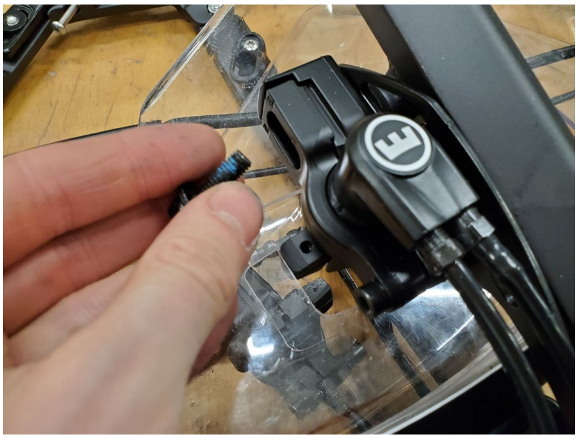
Cable clip	Rear mudguard +rear light + battery cable	
Mud guard bottom bolt	Mudguard + fastening block + Spacer rubber + luggage carrier	

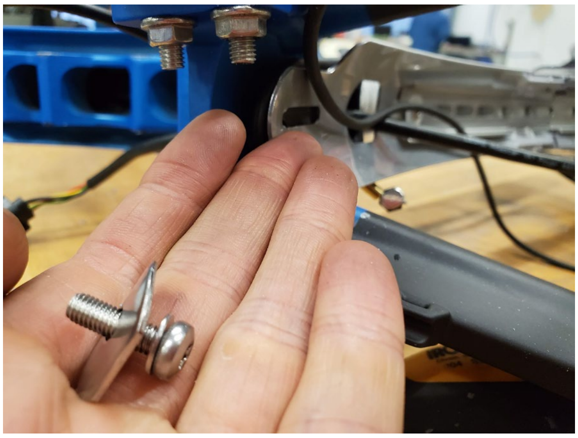
Mud guard top bolt	Mudguard + fastening block + Spacer rubber + luggage carrier	
Right coat protector	Rear mudguard	

Left coat protector	Rear mudguard	
Rear light cable & battery cable	Through the Rear mud guard	
Rear mudguard bolt + washer + two spacers	Luggage carrier, rear mudguard, rear light	

Left binder connector	Luggage carrier	
Right binder connector	Luggage carrier	
Left binder plug	Left binder connector	
Right binder plug	Right binder connector	

User materials tie-wrap (picture shows removal)	User materials + luggage carrier	
Rear mudguard bracket top bolt	Rear mudguard + mudguard bracket	
Rear mudguard bracket bottom bolt	Rear mudguard + mudguard bracket	

Cable guide	Rear mudguard + battery cable + Rear light cable	
Rear brakes bolt	Brakes + Bicycle frame	
Rear mudguard bracket bolt + washer + nut	Frame + Rear mudguard bracket + rear mudguard	

Left luggage carrier bolt	Luggage carrier + frame	
Right luggage carrier bolt	Luggage carrier + frame	
Rear mudguard fastening bolt + washer	Rear mudguard + spacer plastic + frame	

Bicycle frame sub-assembly

Introduction

The bicycle frame sub-assembly initially looks like a good opportunity for automatic assembly since the individual parts are far apart and are generally fastened using bolts either directly into the frame or accompanied by a nut.

Goal
The goal is to understand how the frame sub-assembly can best be assembled taking using linear material placement and fastening using bolts.

Method
The method to reach this goal consists of playing around with the materials and reassembling the subassembly multiple times to understand how the parts interact. Afterwards, an assembly order is chosen which has the least collision of materials.

Results

The frame can be assembled in multiple configurations because the parts do not interact with one another. However, most parts require complex movements due to restricted access originating from the geometry of the bicycle frame itself. A proposed build order is described below and shown in detail in the Bicycle frame sub-assembly video.

Part	Fastened to
Bicycle stand	Frame
Bicycle stand left bolt & nut	Frame + Bicycle stand
Bicycle stand right bolt & nut	Frame + Bicycle stand
Brakes bolt	Frame
Left coat protector clip	Frame
Left coat protector bolt & washer	Frame + Left coat protector clip
Right coat protector clip	Frame
Right coat protector bolt & washer	Frame + Right coat protector clip
Left rear wheel holder	Frame
Left rear nut	Frame + Left rear wheel holder
Left rear bolt	Frame + Left rear wheel holder
Left rear wheel holder nut	Frame + Left rear wheel holder
Left rear wheel holder bolt	Frame + Left rear wheel holder + Left rear wheel holder nut
Left distancing bolt	Frame
Right rear wheel holder	Frame

Right rear nut	Frame + Left rear wheel holder
Right rear bolt	Frame + Left rear wheel holder
Right rear wheel holder nut	Frame + Right rear wheel holder
Right rear wheel holder bolt	Frame + Right rear wheel holder + Right rear wheel holder nut
Right rear cover	Frame + Left rear wheel holder + Left rear nut + Left rear bolt
Right rear cover bolt	Frame + Left rear wheel holder + Left rear nut + Left rear bolt + Left rear cover
Right distancing bolt	Frame
Left rear cover	Frame + Left rear wheel holder + Left rear nut + Left rear bolt
Left rear cover bolt	Frame + Left rear wheel holder + Left rear nut + Left rear bolt + Left rear cover
Right rear cover	Frame + Right rear wheel holder + Right rear nut + Right rear bolt
Right rear cover bolt	Frame + Right rear wheel holder + Right rear nut + Right rear bolt + Right rear cover
Left frame bolt & nut	Frame
Right frame bolt & nut	Frame
Mudguard bracket	Frame
Mudguard bracket bolt & nut	Frame + Mudguard bracket
Sensor + sensor screw	Frame
Sensor rubber dome	Sensor
Sensor clip	Sensor cable
Brake cable bolt	Brake cable holder
Handlebars ring	Frame
Handlebars cover	Frame + Handlebars ring
Handlebars cover screw	Frame + Handlebars cover
Second front light	Frame + Handlebars cover
Left second front light screw	Second front light + Frame
Right second front light screw	Second front light + Frame

Rear mudguard bracket	Frame
Rear mudguard bracket bolt & nut	Frame + Rear mudguard bracket

Conclusion

The bicycle frame can be assembled as a sub-assembly, but automation would be preferable after redesign and relocation of part attachment locations due to previously mentioned restricted access to parts. Therefore, the bicycle frame sub-assembly should not be the starting point of the automation of the bicycle assembly.

Appendix E, Overview of methods used in the initial framework

The initial framework

The initial framework supports various stakeholders in the evaluation and improvement of assembly lines. This is done by guiding the stakeholder through the various levels of the assembly line, as described in figure 1. To cover the variety of stakeholders, a variety of methods is proposed per analysis and ideation level. These methods originate from the Delft Design guide (Zijlstra & van der Schoor, 2014), and are depicted in figure 5 to 14 on the following pages on cards.

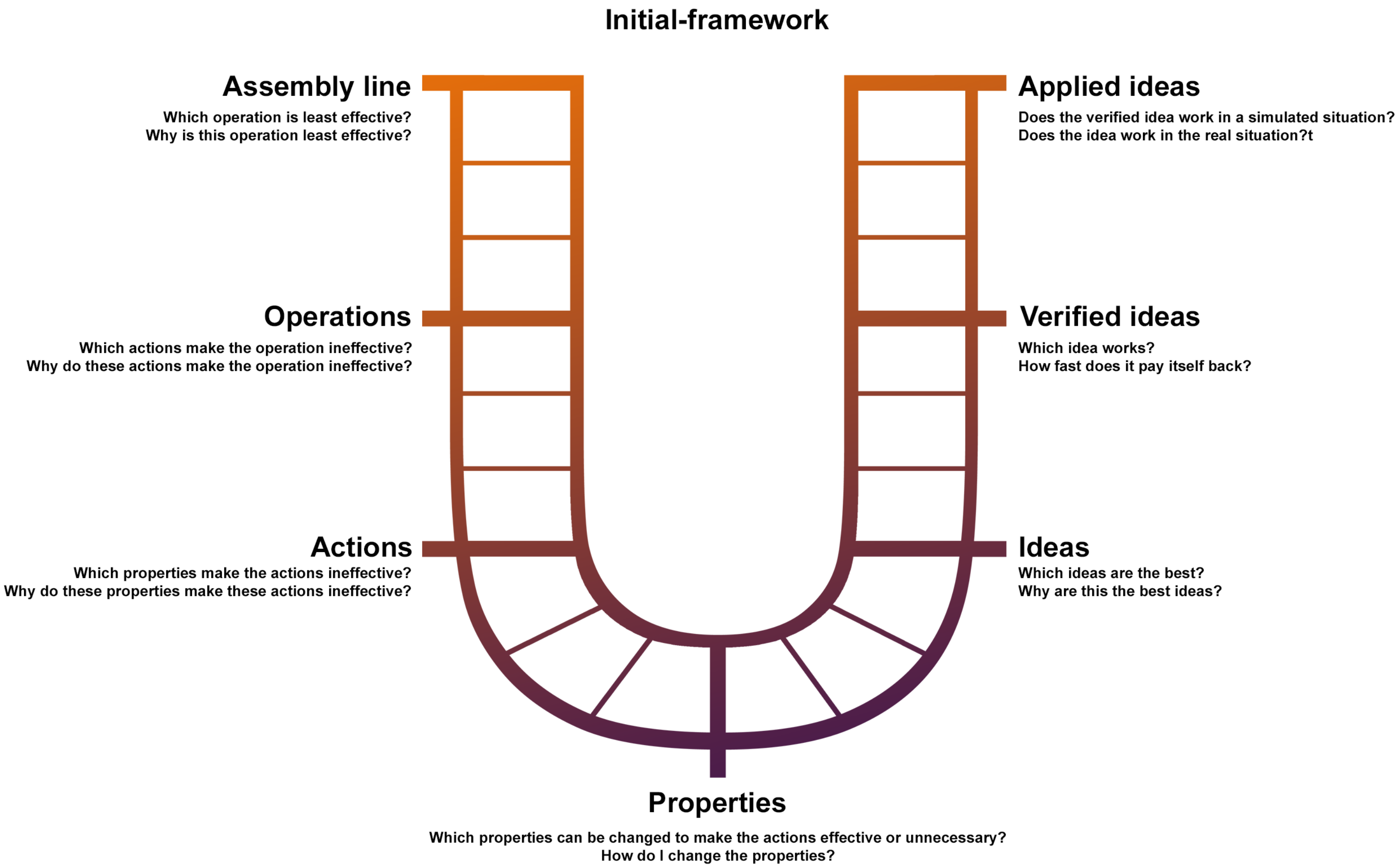


Figure 1 Overview of the initial framework

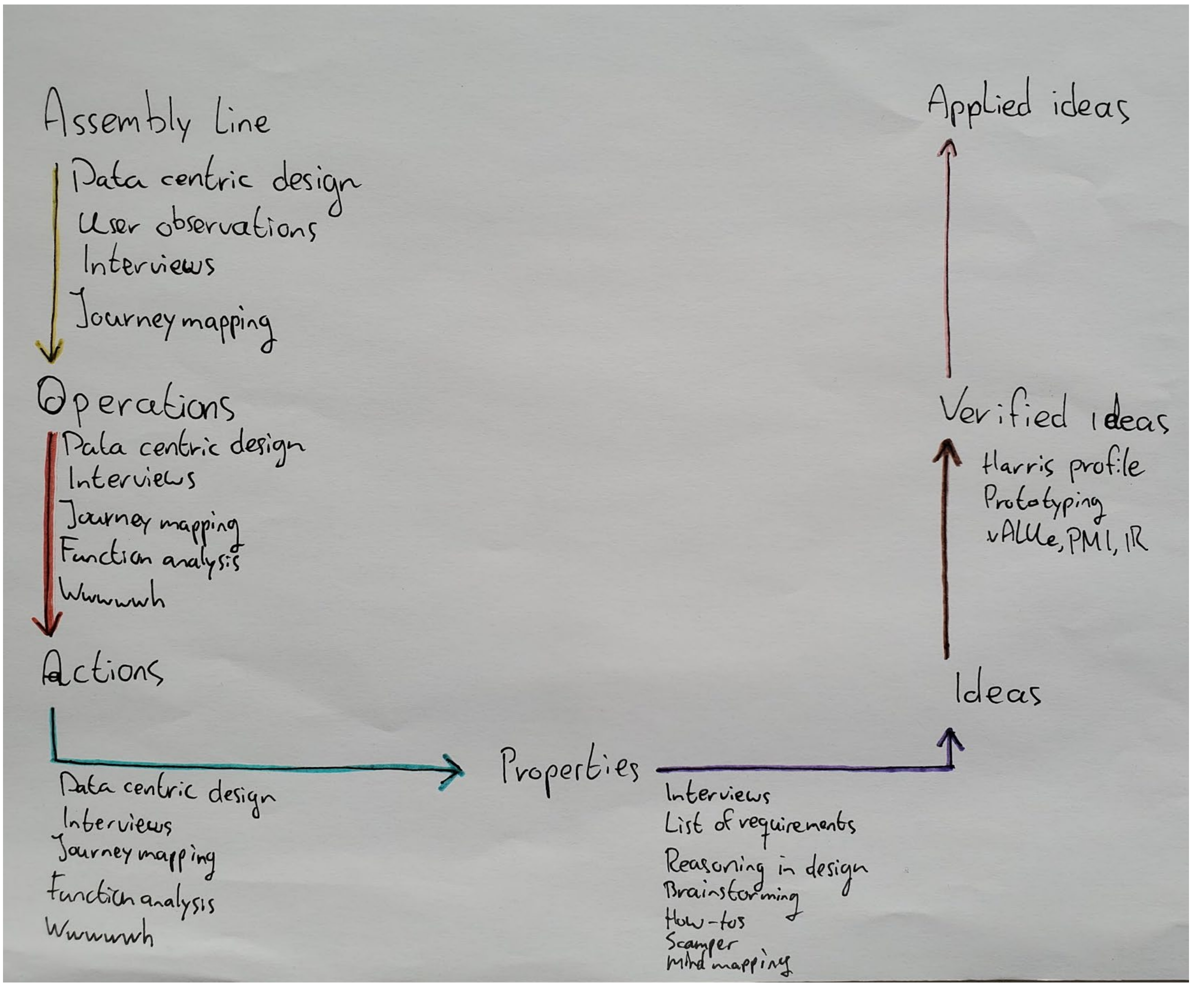


Figure 2 The methods in the initial framework

Figure 3 An overview of the initial framework and related methods.

Figure 4 An overview of the methods used in the initial framework.

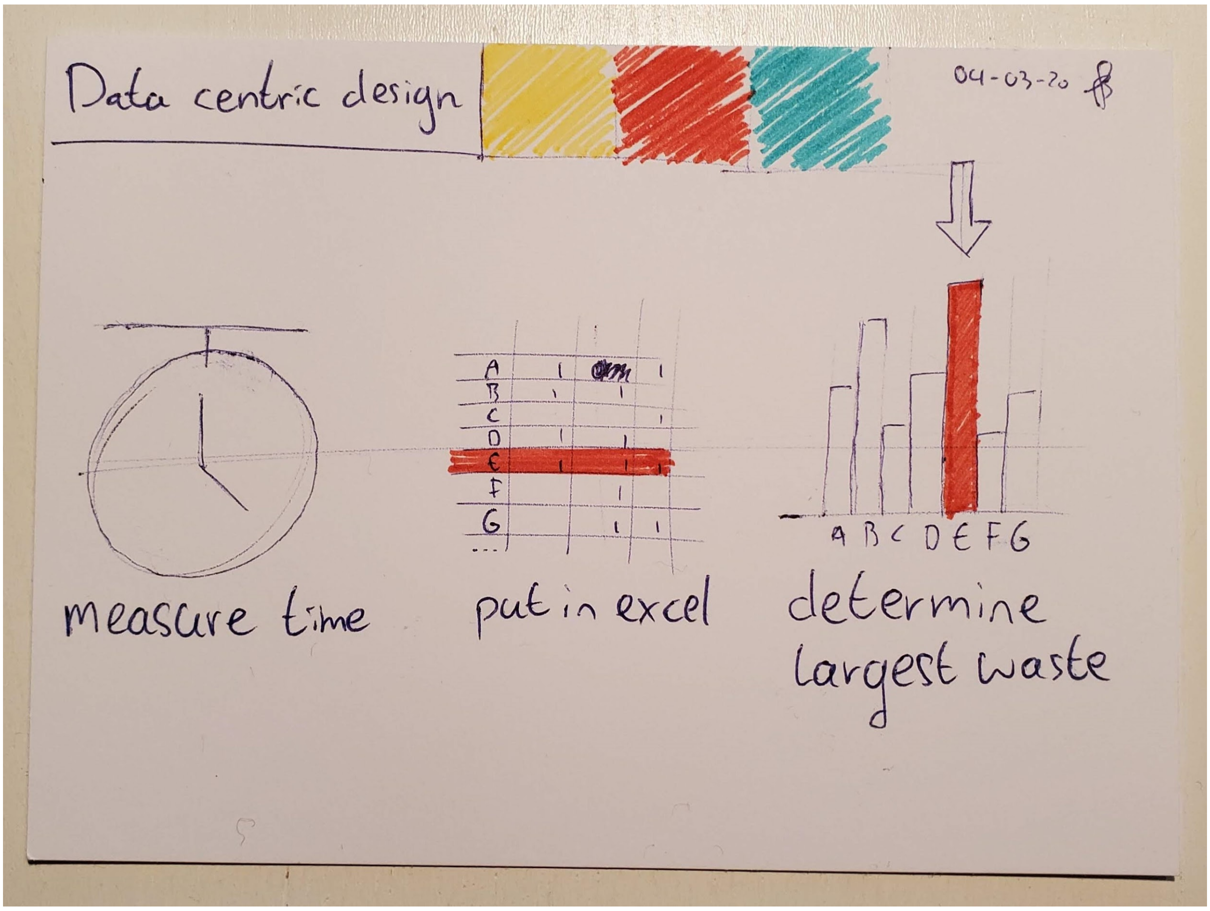


Figure 5 Data centric design card, usable in the assembly line, operation and action steps.

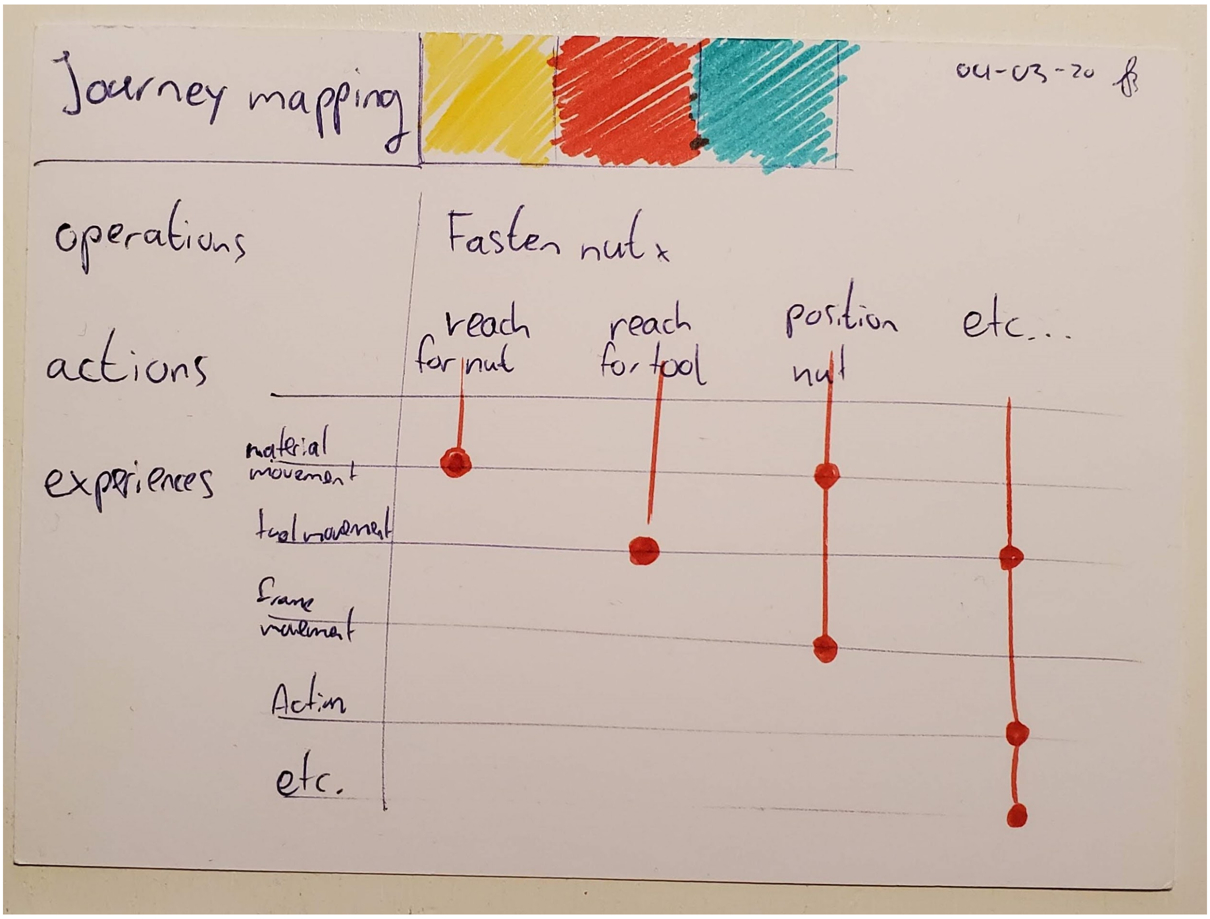


Figure 6 Journey mapping card, usable in the assembly line, operation and action steps.

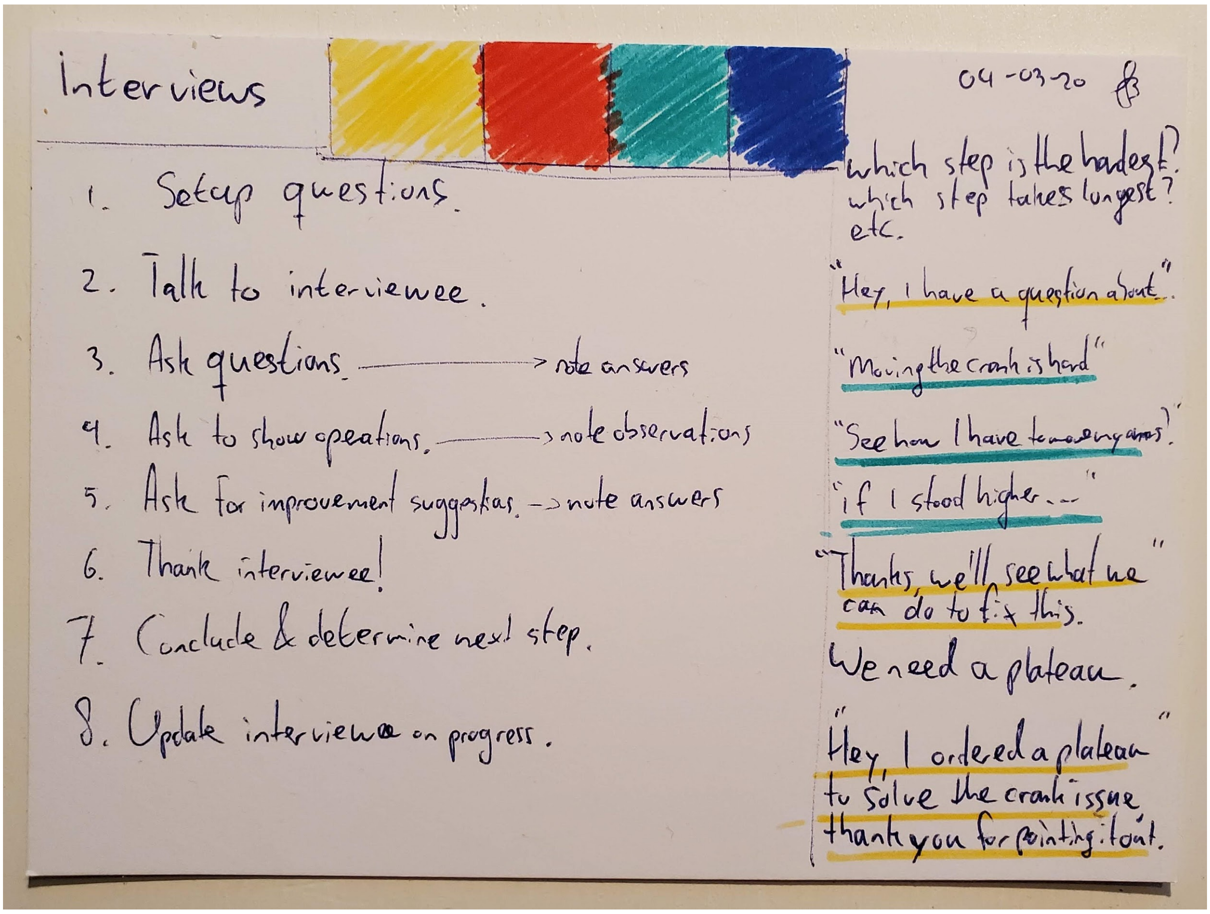


Figure 7 Interviews card, usable in the assembly line, operation, action and ideation steps.

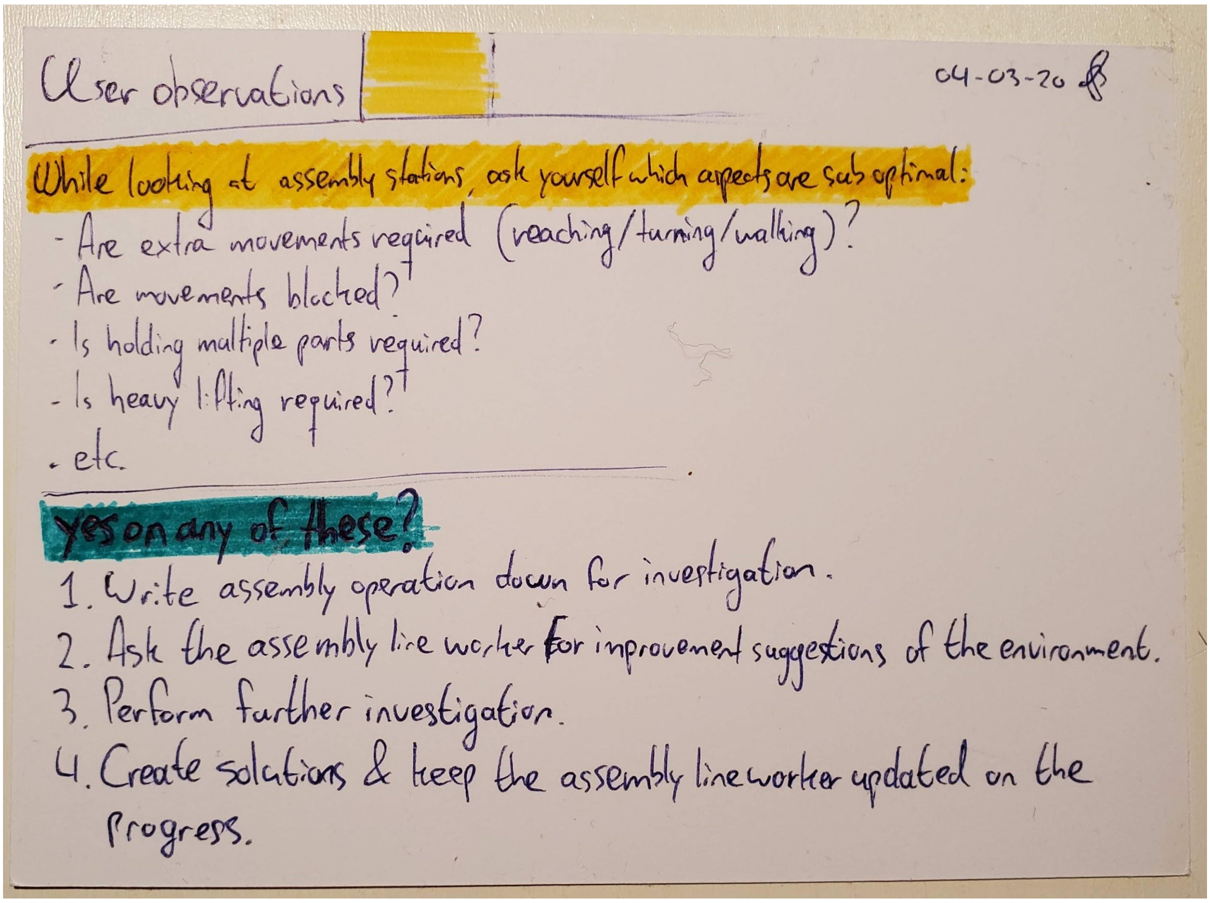


Figure 8 User observations card, which can be used to identify the assembly line level.

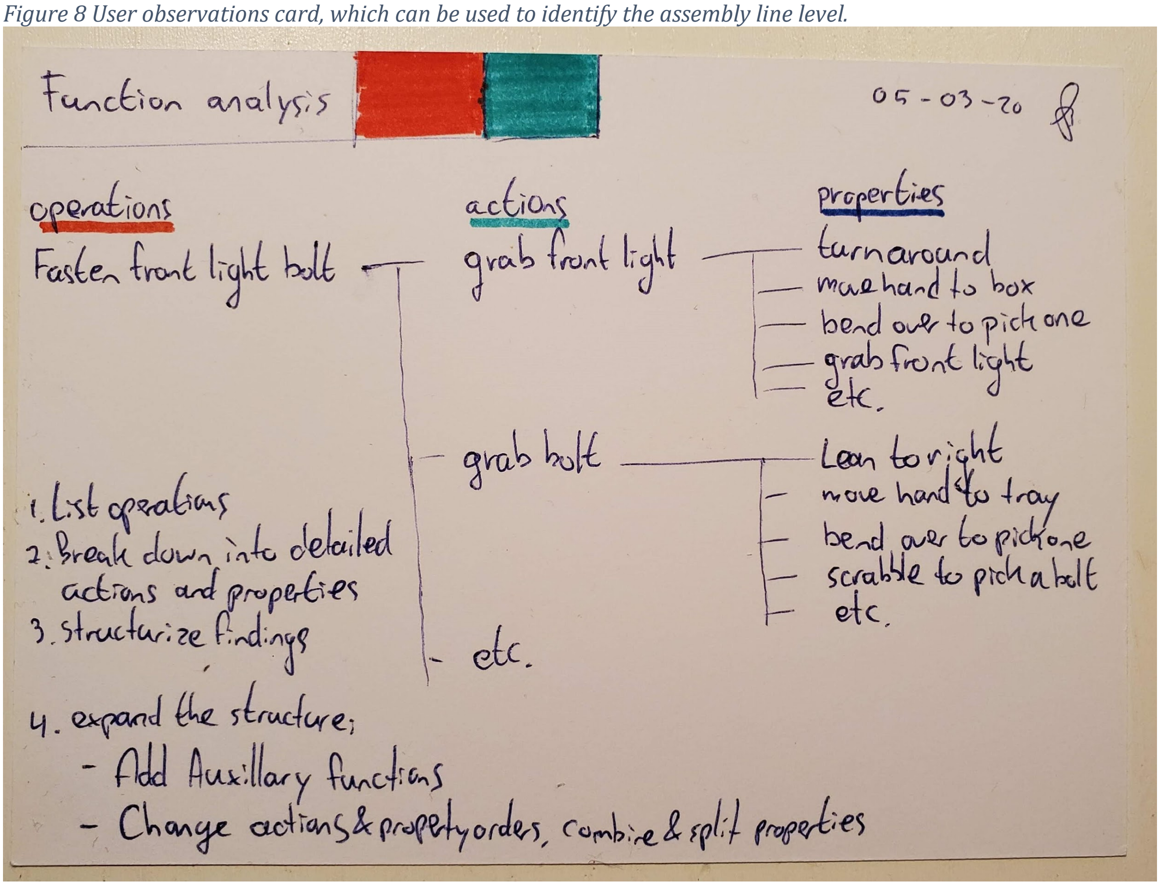


Figure 9 Function analysis card, usable to investigate the actions and movements of the assembly line.

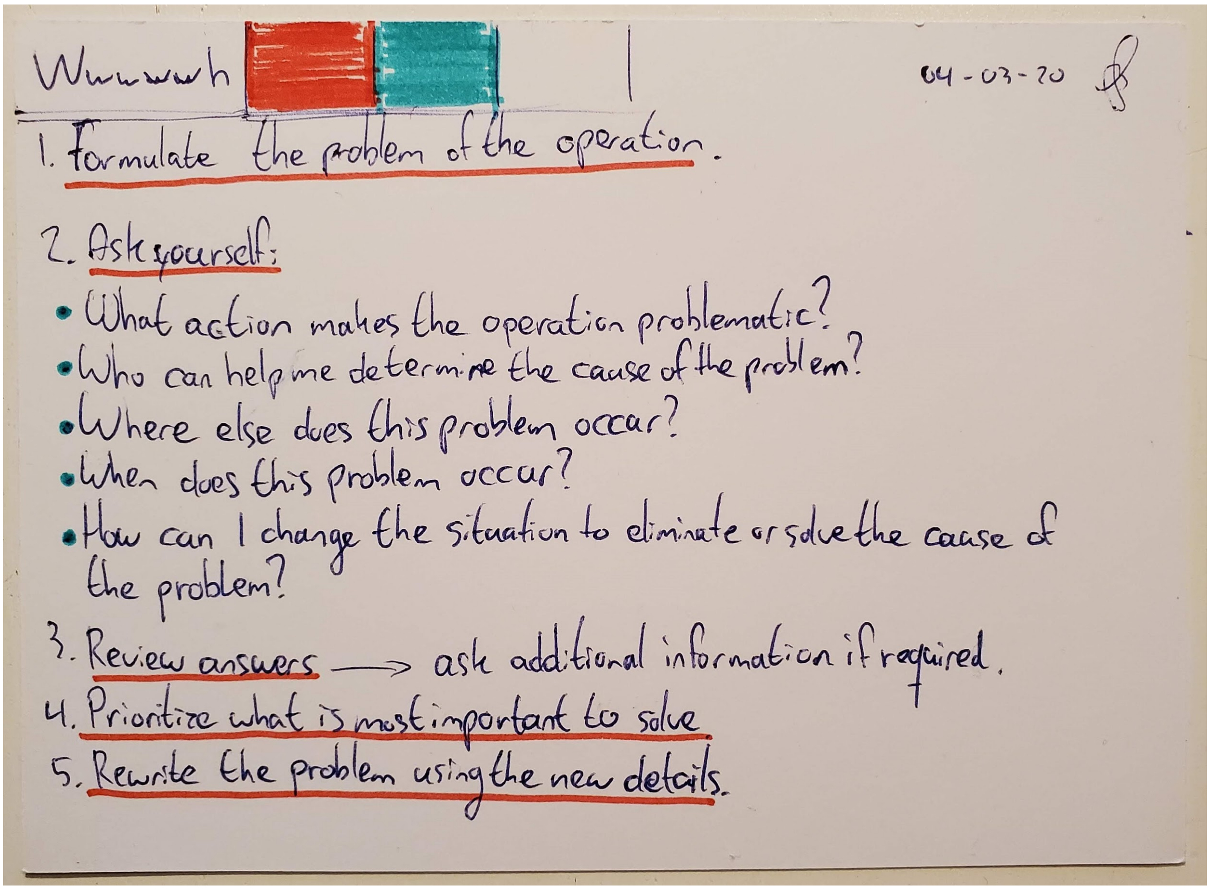


Figure 10 The Wwwwwh method, a method to improve the found problems at the assembly line.

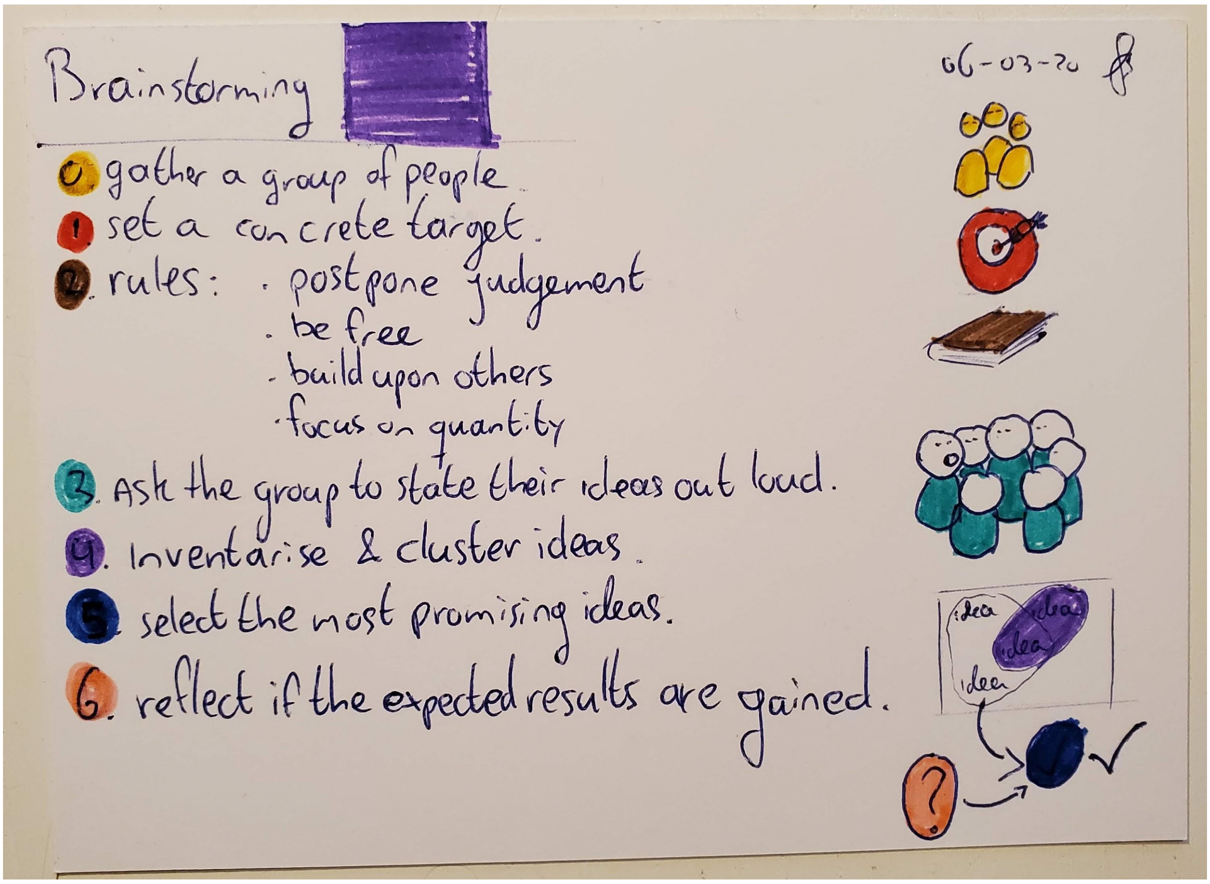


Figure 11 Brainstorming card, which can be used to ideate solutions for the found assembly problems.

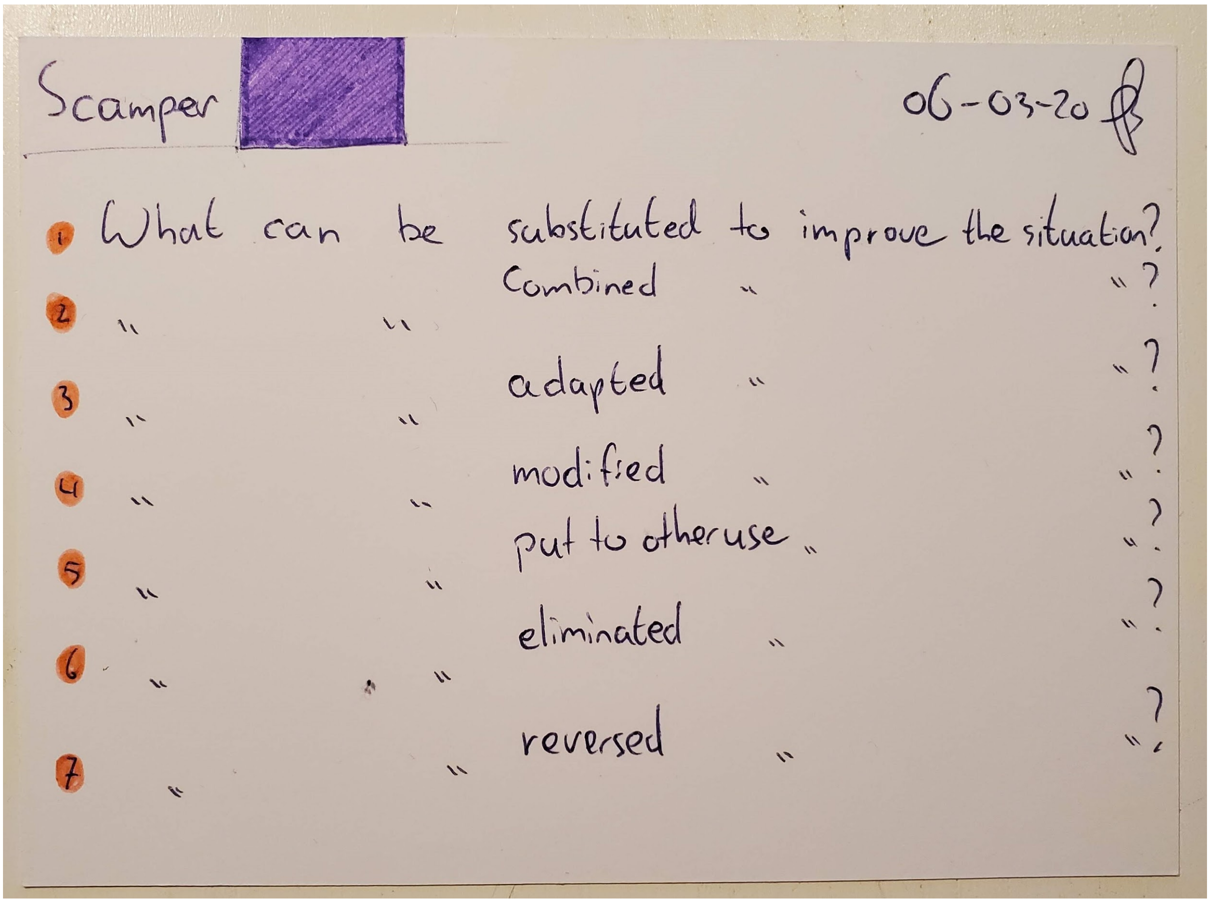


Figure 12 Scamper, an ideation method to ideate solutions for found assembly problems.

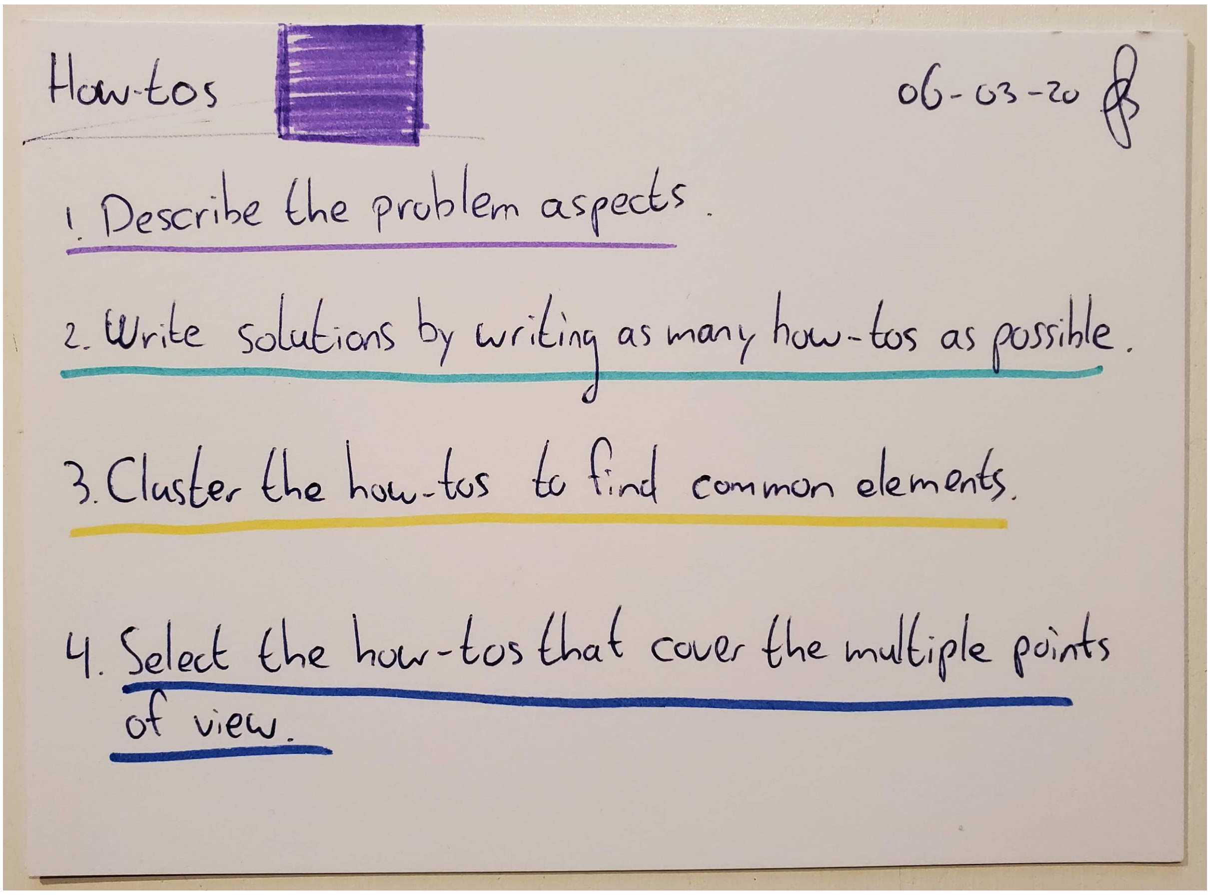


Figure 13 How to-s, an ideation method to ideate solutions for found assembly problems.

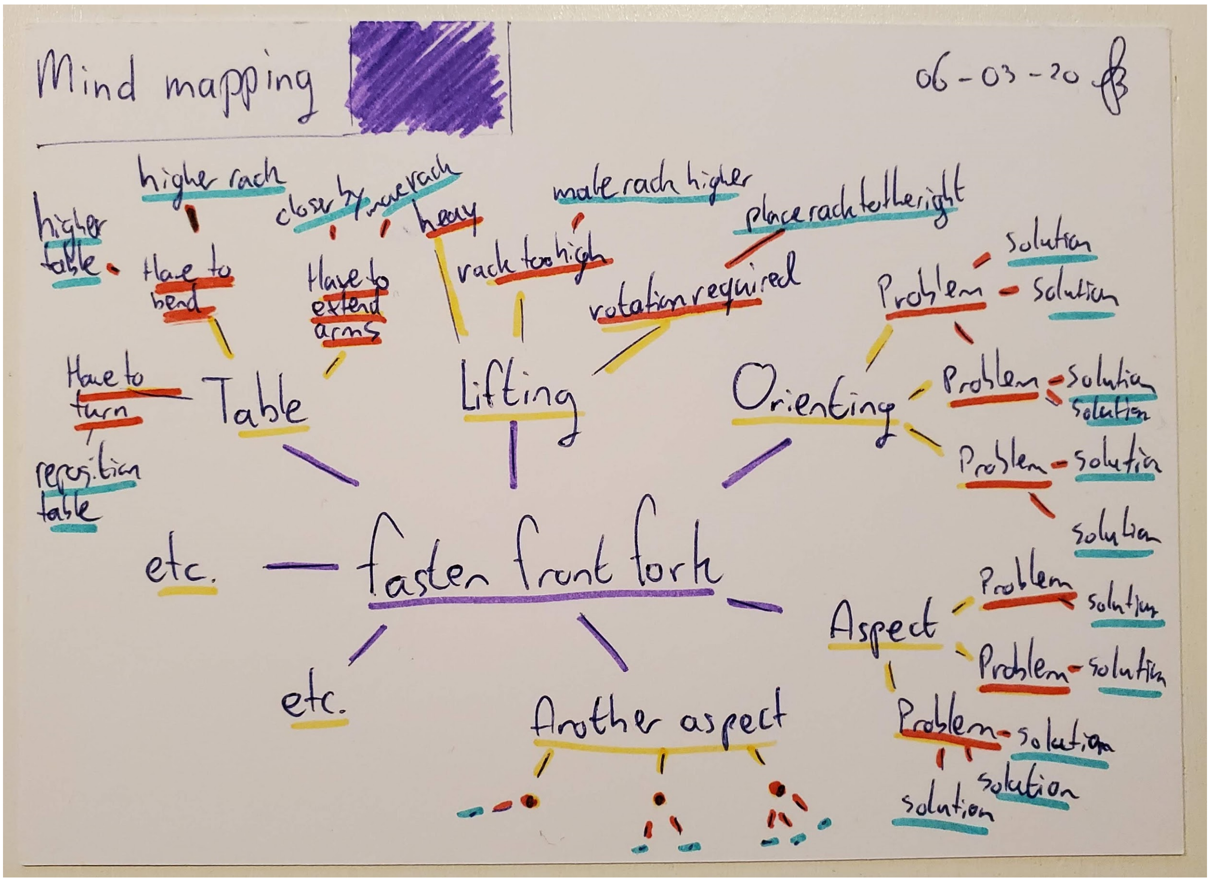


Figure 14 Mind mapping, an ideation method to ideate solutions for found assembly problems.

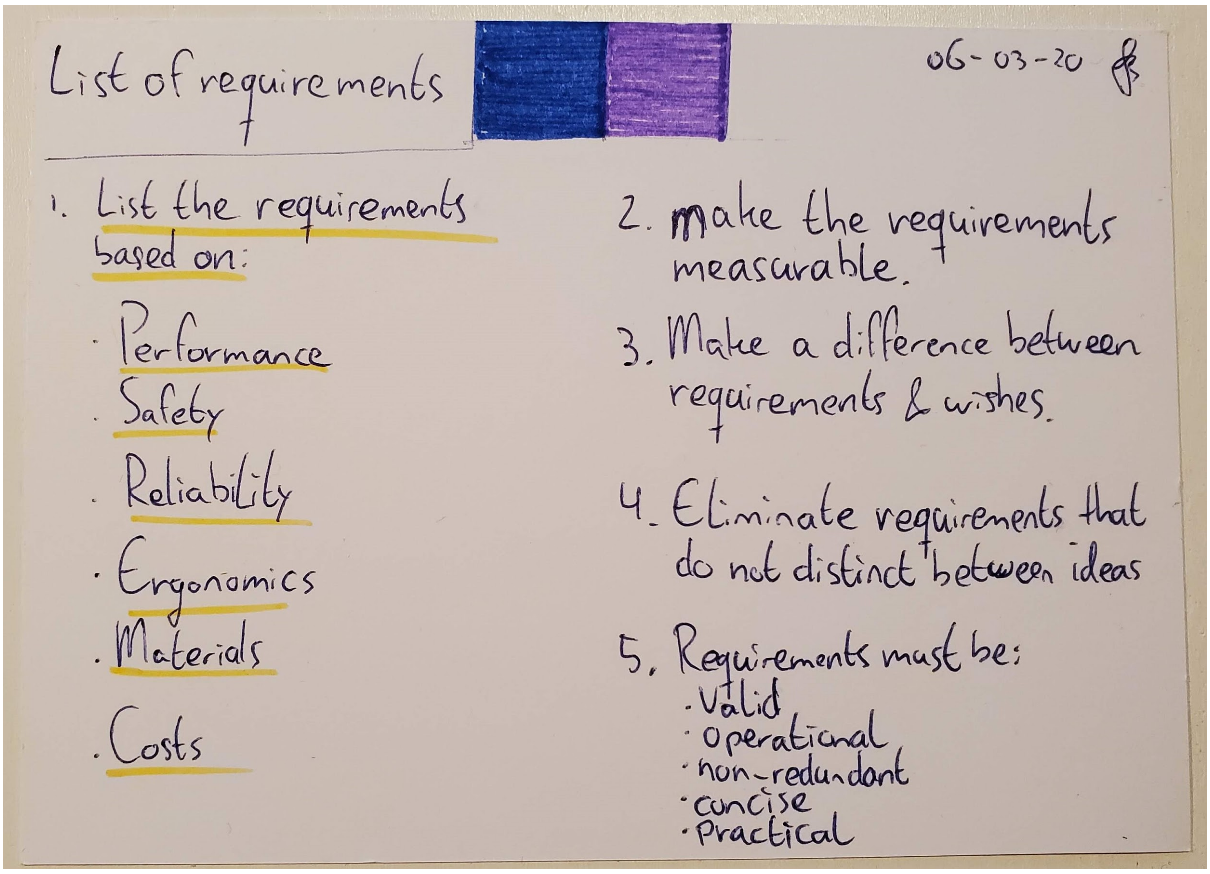


Figure 15 List of requirements, a method to define what aspects of the assembly line must be improved and to verify the solutions found..

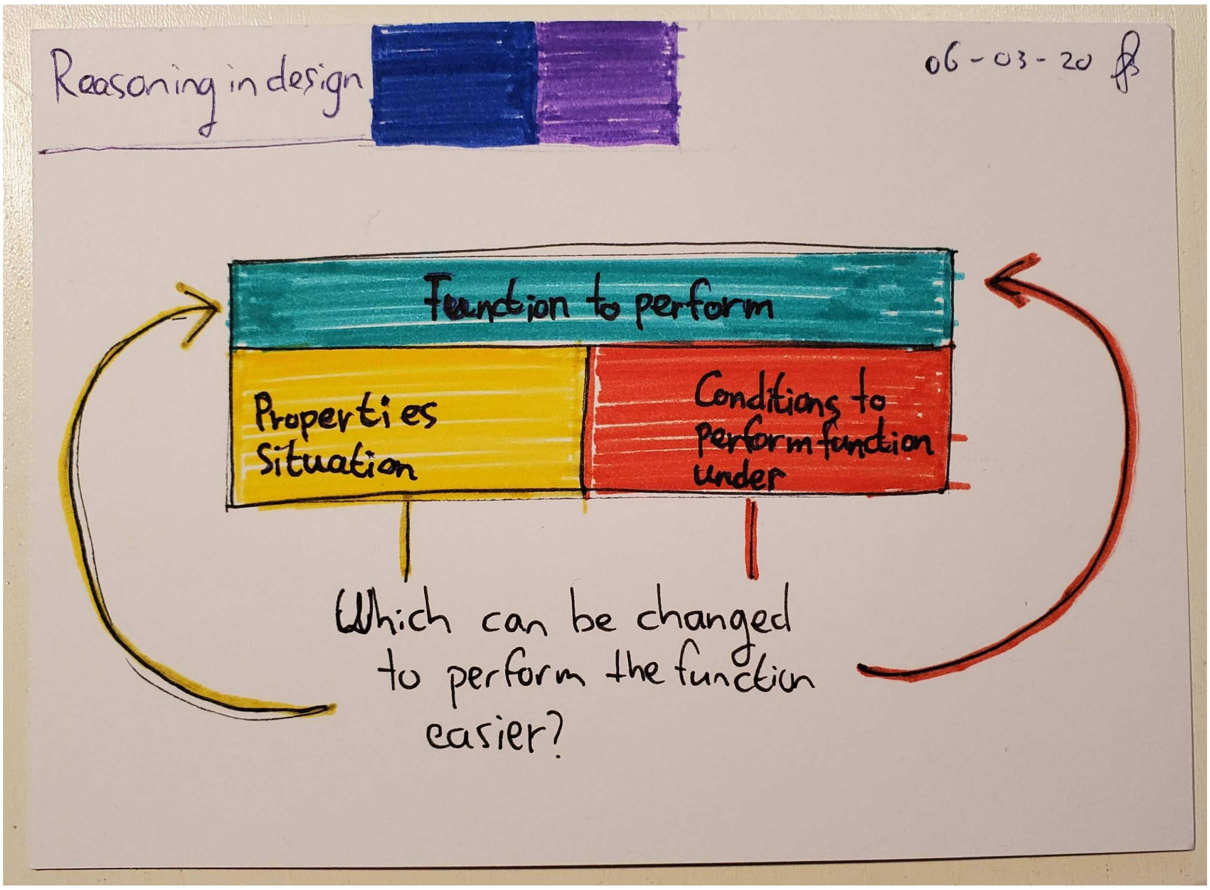


Figure 16 Reasoning in design, a method to ideate and verify improvements.

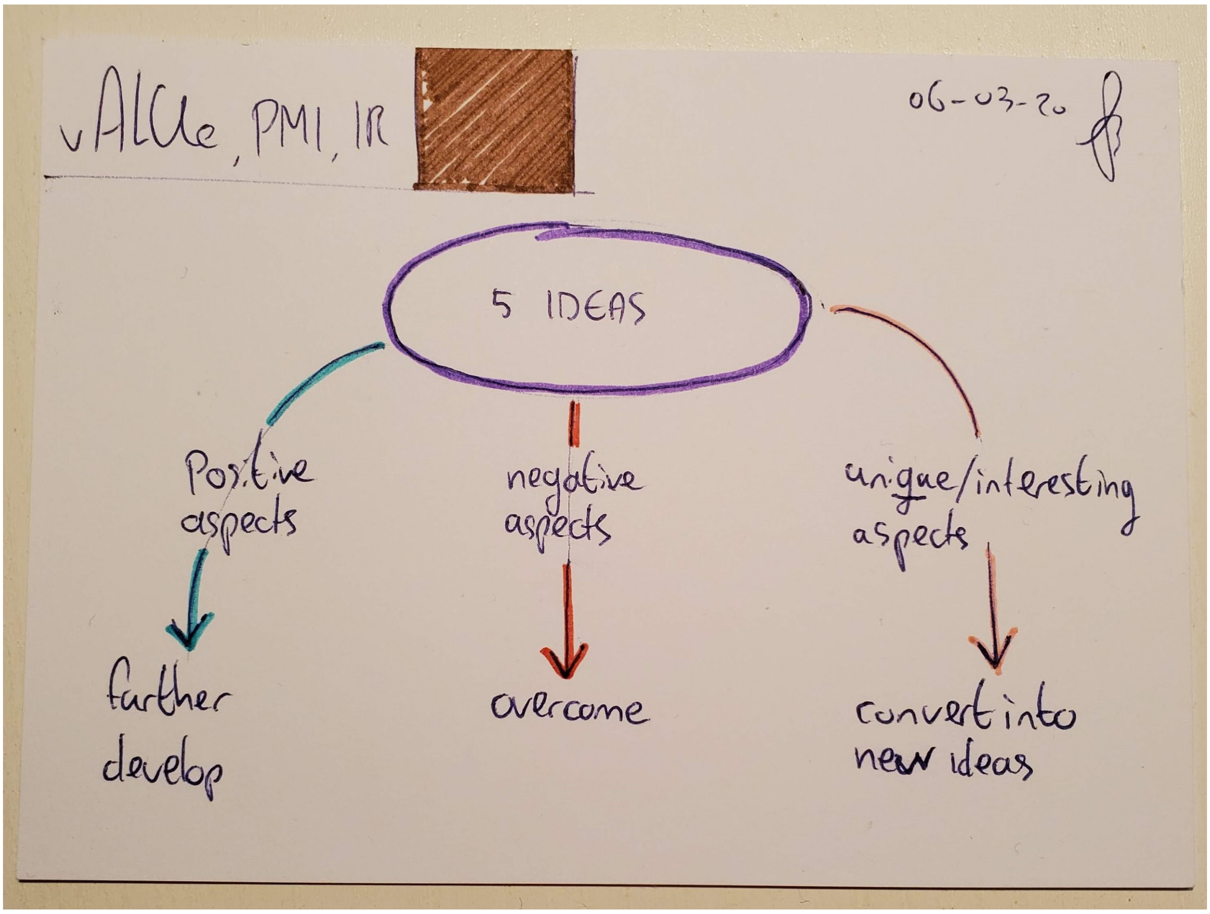


Figure 17 vALUe, PMI,Ir methods, used to find out which ideas are worth pursuing.

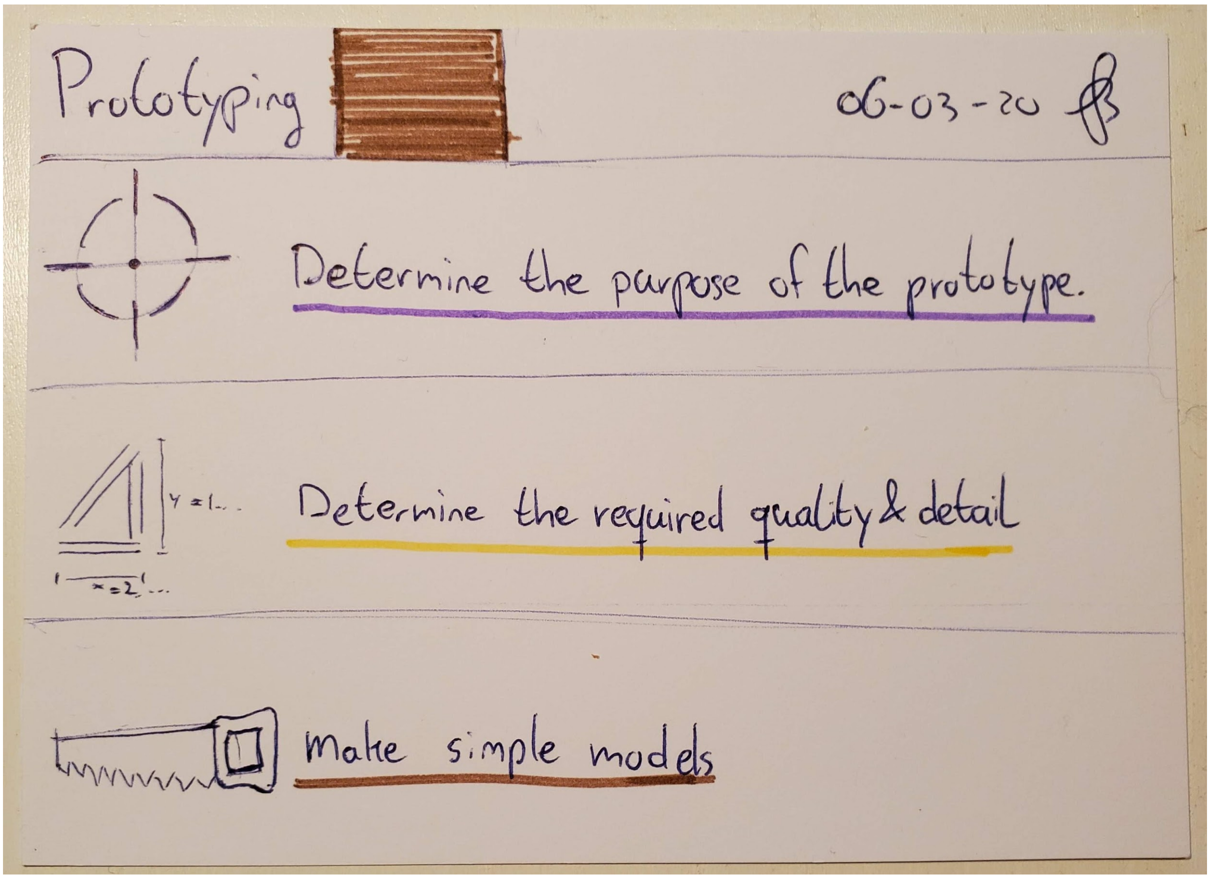


Figure 18 Prototyping, build examples to find out if the ideas are valid.

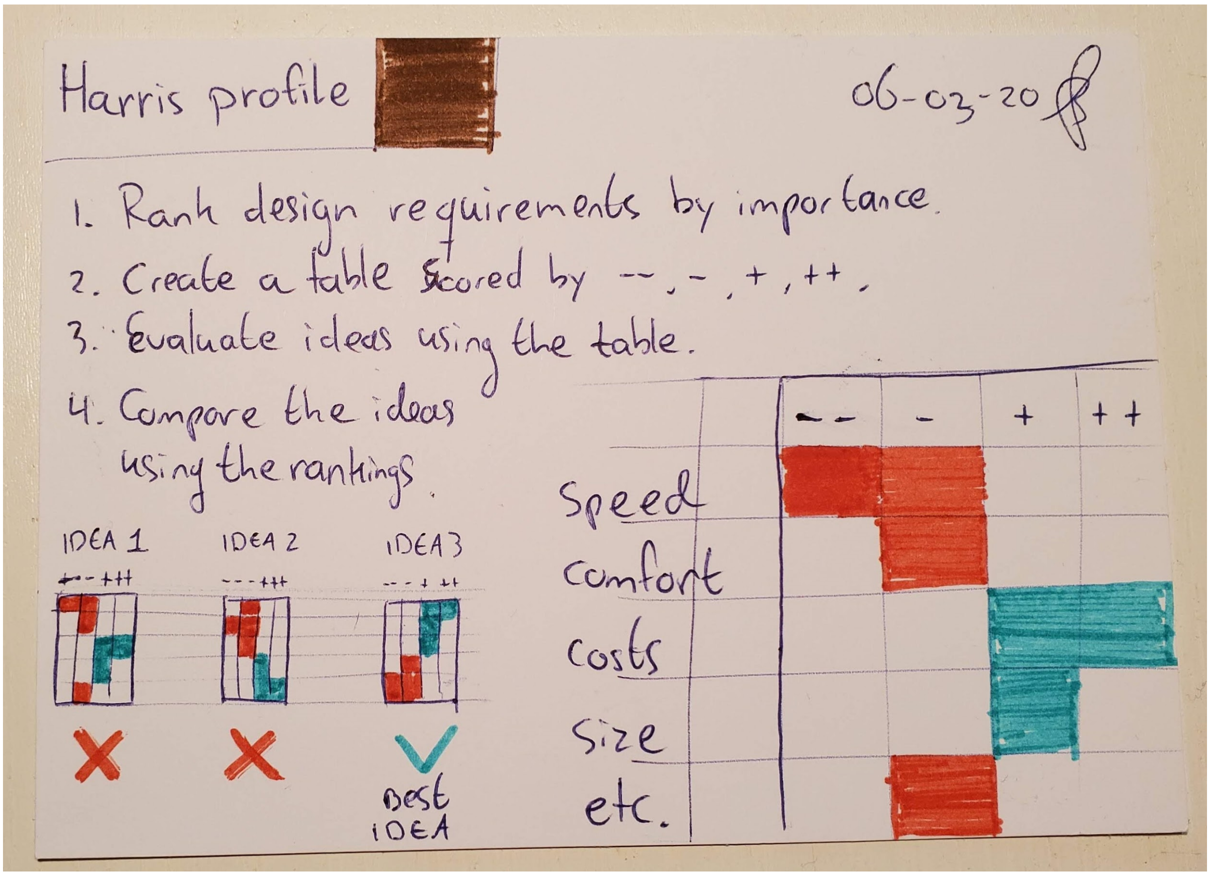
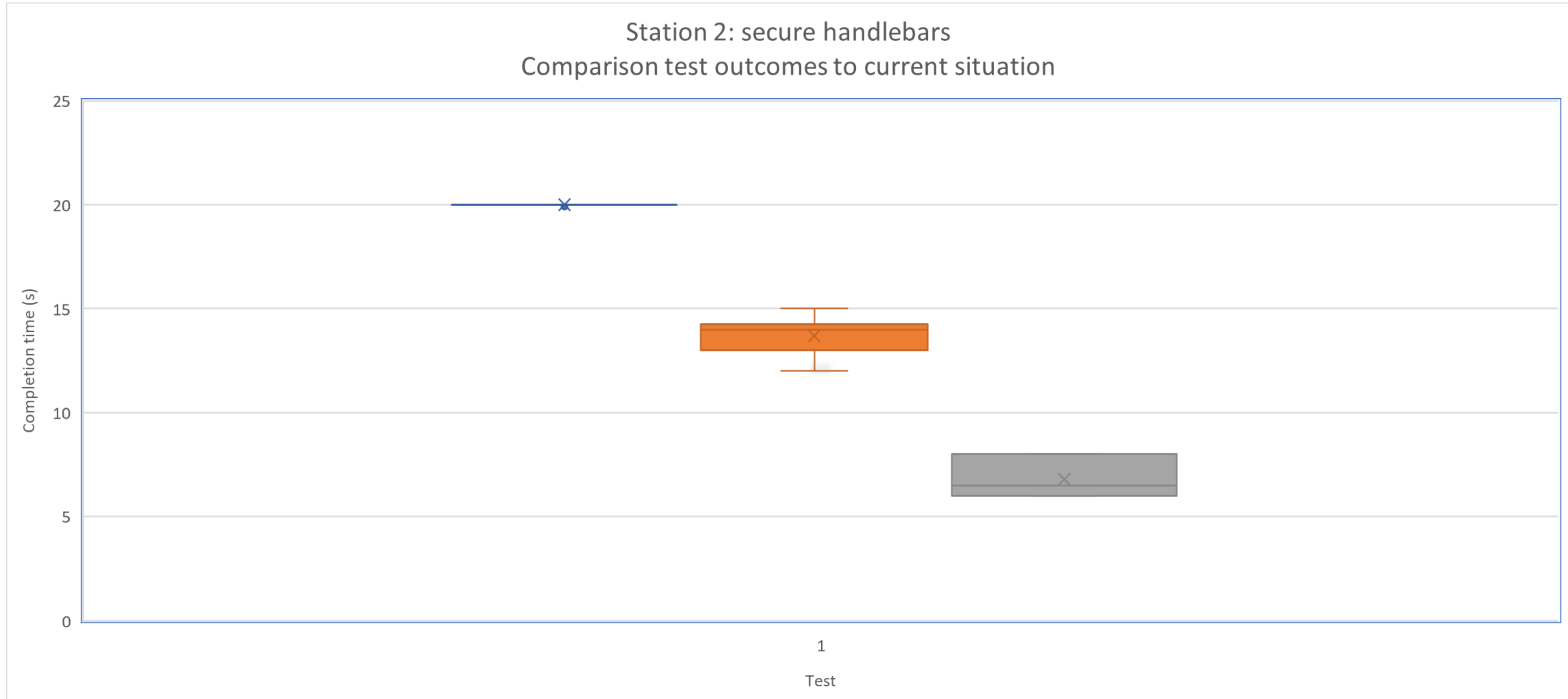


Figure 19 Harris profile, used to select ideas.

Appendix L: the results of tests at station 2. In this and the next datasheet, the outcomes of the assembly line improvement test for station 2 are detailed.

		Start	Stop	Time required
Station_2_original_operation				
	1	0	20	20
	2	0	20	20
	3	0	20	20
	4	0	20	20
	5	0	20	20
	6	0	20	20
	7	0	20	20
	8	0	20	20
	9	0	20	20
	10	0	20	20
Station_2_handlebars_open				
	1	13	27	14
	2	46	59	13
	3	88	102	14
	4	119	132	13
	5	150	164	14
	6	183	198	15
	7	213	225	12
	8	242	255	13
	9	273	288	15
	10	307	321	14
Station_2_handlebars_open_layout_changed				
	1	20	28	8
	2	43	49	6
	3	78	84	6
	4	98	104	6
	5	115	122	7
	6	131	138	7
	7	147	153	6
	8	162	168	6
	9	185	193	8
	10	205	213	8



Comparison time required		Original operation	Handlebars open	Handlebars open layout changed
	1	19.9	14	8
	2	20.1	13	6
	3	20	14	6
	4	20	13	6
	5	20	14	7
	6	20	15	7
	7	20	12	6
	8	20	13	6
	9	20	15	8
	10	20	14	8
Mean		**20**	**13.7**	**6.8**
Standard deviation			0.948683298	0.918936583
Median			14	6.5

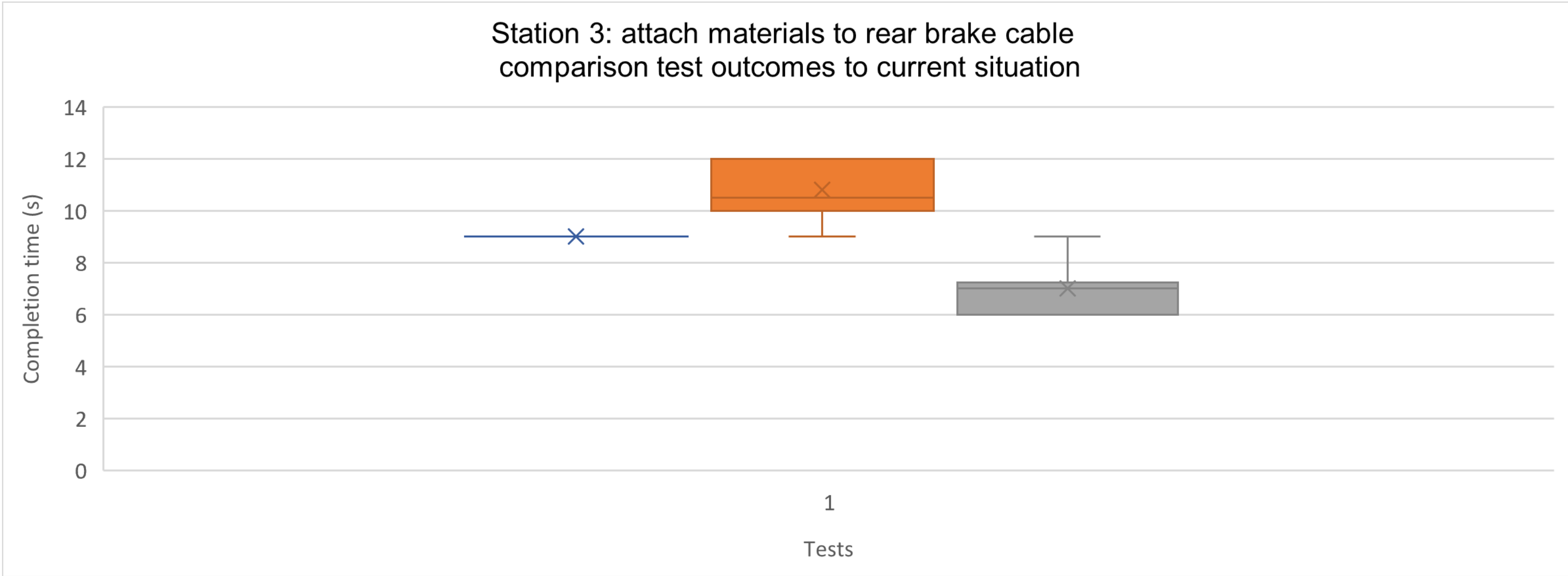
t-Test: Two-Sample Assuming Unequal Variances

	Handlebars open	*Handlebars open + layout changed*
Mean	13.7	6.8
Variance	0.9	0.844444444
Observations	10	10
Hypothesized Mean Difference	0	
df	18	
t Stat	16.52039851	
P(T<=t) one-tail	1.26804E-12	
t Critical one-tail	1.734063607	
P(T<=t) two-tail	2.53609E-12	
t Critical two-tail	2.10092204	

Video footage	Number	End time action	Action	Movement description		
Assembly station 2:	2.1	2	Turn to grab handlebars	Turn around and take three steps to move from assembly location to handlebar supply rack.	R2.1	Assemblers must not be required to turn to pick up materials.
					R2.27	Assemblers must not be required to perform steps.
Current situation	2.2	3	Bend forward for grabbing handlebars	Bend forward and reach with left arm to grasp handlebar from handlebar supply rack.	R2.2	Assemblers must not be required to reach for materials.
					R2.11	Assemblers must not be required to work in awkward static/dynamic trunk postures.
	2.3	4	Lifting handlebars from rack	Vertically lift handlebar from handlebar supply rack.	R1.5	The assembly movements must be performed without objects obstructing the simplest assembly movement.
					R2.4	Assemblers must not be required to lift materials.
	2.4	6	Move handlebars to openable orientation	Turn around and take one step while holding handlebars.	R2.1	Assemblers must not be required to turn to pick up materials.
					R2.27	Assemblers must not be required to perform steps.
					R2.5	Parts must not require preparation at the assembly line.
	2.5	13	Open & adjust handlebars	Turn, take one step, open handlbars and change handlebar inner orientation.	R1.1	Parts must not require preparation at the assembly line.
					R1.4	Parts must not require restructuring or opening.
					R2.10	Assemblers must not be required to stand without effective relief.
					R2.16	Assemblers must not be required to work involving high exertion.
					R2.23	The degree of physical strain to which workers are exposed should be minimized.
	2.6	15	Turn, grab & orient screwdriver	Turn, grab automated screwdriver and orient screwdriver in handlebars.	R1.6	Parts must be oriented in one motion to their assembly positions by the assembler.
					R2.1	Assemblers must not be required to turn to pick up materials.
					R2.2	Assemblers must not be required to reach for materials.
					R2.5	Assemblers must not be required to carry materials.
					R2.10	Assemblers must not be required to stand without effective relief.
	2.7	17	Correct bolt orientation on handlebars	Take two steps, reposition sidebolt on handlebars.	R1.1	Parts must not require preparation at the assembly line.
					R1.2	Parts must not require correction or rework during and after assembly.
					R1.6	Parts must be oriented in one motion to their assembly positions by the assembler.
					R2.3	Assemblers must not be required to reorient materials.
					R2.27	Assemblers must not be required to perform steps.
	2.8	20	Step over setup to orient handlebars	Take three steps forward towards assembly location and orient handlebars and automated screwdrive	R1.5	The assembly movements must be performed without objects obstructing the simplest assembly movement.
					R2.27	Assemblers must not be required to perform steps.
Assembly station 2:	2.a	1	Grab automated screwdriver.	Reach forward and grab automated screwdriver.	R2.2	Assemblers must not be required to reach for materials.
Handlebars open	2.b	2	Place screwdriver on table.	Turn, step over frame holder and place the automated screwdriver on the lower table.	R2.1	Assemblers must not be required to turn to pick up materials.
					R2.27	Assemblers must not be required to perform steps.
	2.c	5	Grab handlebars	Take two steps and grab handlebars.	R2.27	Assemblers must not be required to perform steps.
	2.d	6	Lift handlebars and change hands.	Lift handlebars and change handlebars to left hand.	R2.3	Assemblers must not be required to reorient materials.
	2.e	8	Grab automated screwdriver.	Take three steps and reach to grab the automated screwdriver.	R2.2	Assemblers must not be required to reach for materials.
					R2.27	Assemblers must not be required to perform steps.
	2.f	10	Move to assembly location.	Take one step and one additional step over the frame holder.	R2.27	Assemblers must not be required to perform steps.
	2.g	11	Orient automated screwdriver in handlebars.	Orient automated screwdriver in handlebars.	-	
	2.h	14	Orient handlebars on bicycle frame.	Orient the handlebars on the bicycle frame.	-	
Assembly station 2:	2.i	1	Grab screwdriver.	Reach forward and grab automated screwdriver.	R2.2	Assemblers must not be required to reach for materials.
handlebars open	2.j	2	Turn and reach for handlebars.	Turn and reach for handlebars.	R2.2	Assemblers must not be required to reach for materials.
					R2.1	Assemblers must not be required to turn to pick up materials.
and	2.k	3	Grab handlebars.	Grab and lift handlebars.	-	
relocated handlebars	2.l	4	Orient screwdriver in handlebars.	Turn and orient automated screwdriver in handlebars.	R2.1	Assemblers must not be required to turn to pick up materials.
supply	2.m	6	Orient handlebars on bicycle frame.	Orient handlebars on bicycle frame.	-	

Appendix M: the results of tests at station 3. In this and the next datasheet, the outcomes of the assembly line improvement test for station 2 are detailed.

Station_3_original_operation		Start	Stop	Time required
	1	1	10	9
	2	1	10	9
	3	1	10	9
	4	1	10	9
	5	1	10	9
	6	1	10	9
	7	1	10	9
	8	1	10	9
	9	1	10	9
	10	1	10	9
Station_3_reconstructed_layout				
	1	4	16	12
	2	23	34	11
	3	66	78	12
	4	85	95	10
	5	103	112	9
	6	120	132	12
	7	138	150	12
	8	157	167	10
	9	173	183	10
	10	190	200	10
Station_3_relocated_bins				
	1	36	43	7
	2	49	55	6
	3	62	69	7
	4	76	82	6
	5	88	95	7
	6	108	115	7
	7	121	129	8
	8	137	144	7
	9	151	157	6
	10	163	172	9



Comparison time required		Original op	Reconstruc	Relocated bins
	1	9	12	7
	2	9	11	6
	3	9	12	7
	4	9	10	6
	5	9	9	7
	6	9	12	7
	7	9	12	8
	8	9	10	7
	9	9	10	6
	10	9	10	9
Average		**9**	**10.8**	**7**
Standard deviation			1.135292	0.942809
Median			10.5	7

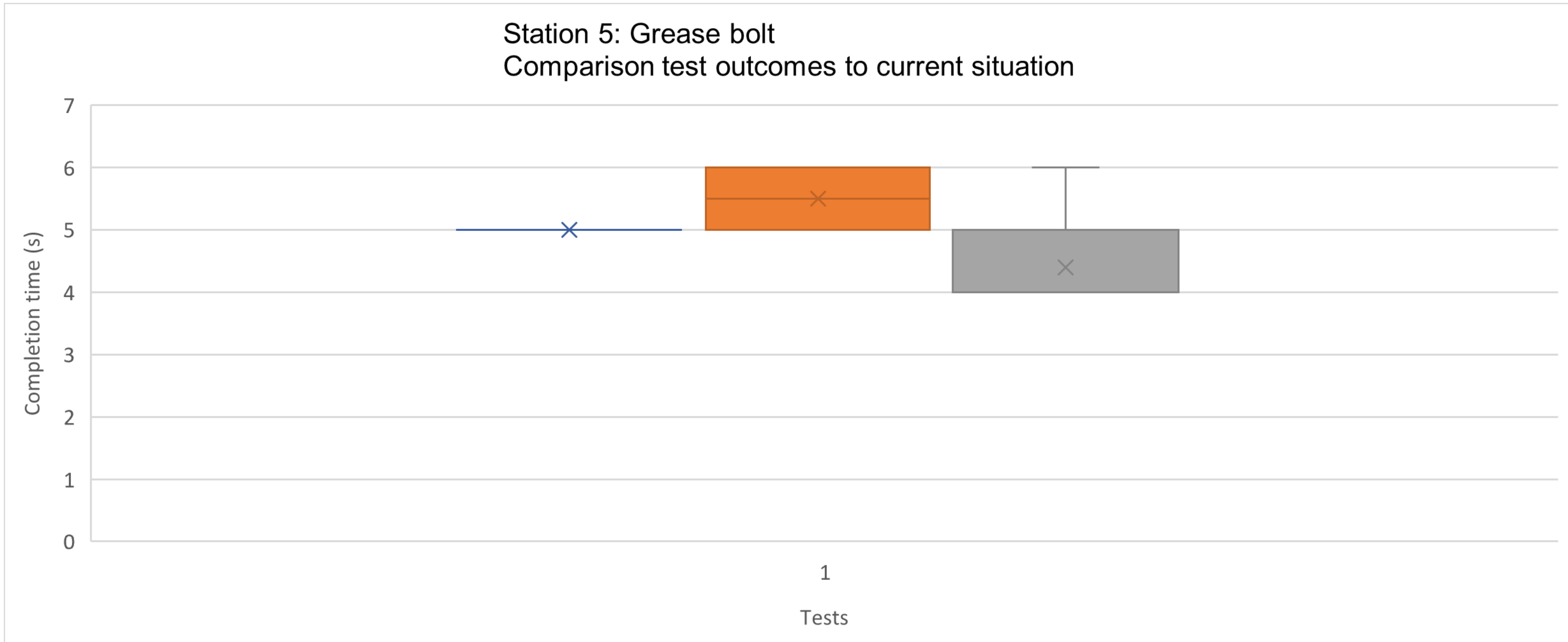
t-Test: Two-Sample Assuming Unequal Variances

	Reconstructed assembly situation	*Relocated bins*
Mean	10.8	7
Variance	1.288888889	0.888888889
Observations	10	10
Hypothesized Mean Difference	0	
df	17	
t Stat	8.142857143	
P(T<=t) one-tail	1.43295E-07	
t Critical one-tail	1.739606726	
P(T<=t) two-tail	2.86591E-07	
t Critical two-tail	2.109815578	

Video footage	Number	End time	Action	Movement description	Requirements	
Assembly line video	3.1	1	Turn towards frame	Drop cablecutter and turn body from materal location to bicycle frame.	R2.1	Assemblers must not be required to turn to pick up materials.
	3.2	3	Turn and reach for cable cover	Grab cable cover by turning and reaching from bicycle frame to material location.	R2.1	Assemblers must not be required to turn to pick up materials.
					R2.2	Assemblers must not be required to reach for materials.
	3.3	4	Slide cable cover over break cable	Place cable cover over cable after turning from material location to bicycle frame.	R2.1	Assemblers must not be required to turn to pick up materials.
	3.4	8	Turn and reach for ring and hollow bolt	Grab ring and bolt by turning and reaching from bicycle frame to material location.	R2.1	Assemblers must not be required to turn to pick up materials.
					R2.2	Assemblers must not be required to reach for materials.
	3.5	9	Slide hollow bolt and ring over break cable	Place ring and bolt over cable after turning from material location to bicycle frame.	R2.1	Assemblers must not be required to turn to pick up materials.
Reconstructed assembly situation	3.a	1	Grab cable cover.	Grab cable cover by leaning sideways.	R2.2	Assemblers must not be required to reach for materials.
	3.b	4	Place cable cover over cable.	Attach cable cover by turning and leaning.	R2.1	Assemblers must not be required to turn to pick up materials.
					R2.2	Assemblers must not be required to reach for materials.
	3.c	5	Grab hollow bolt.	Grab hollow bolt by leaning sideways.	R2.2	Assemblers must not be required to reach for materials.
	3.d	7	Grab ring.	Grab ring by leaning sideways.	R2.2	Assemblers must not be required to reach for materials.
	3.e	12	Place hollow bolt and ring on cable.	Place hollow bolt and ring on cable by turning and leaning.	R2.2	Assemblers must not be required to reach for materials.
					R2.1	Assemblers must not be required to turn to pick up materials.
Close layout	3.f	1	Grab cable cover and ring.	Grab cable cover and ring.	-	
	3.g	2	Grab hollow bolt.	Grab hollow bolt.	-	
	3.h	6	Place cable cover, ring and hollow bolt on cable.	Place cable cover, ring and hollow bolt on cable.	-	

Appendix N: the results of tests at station 3. In this and the next datasheet, the outcomes of the assembly line improvement test for station 5 are detailed.

Station_5_original_operation	Start	Stop	Time required
1	78	83	5
2	78	83	5
3	78	83	5
4	78	83	5
5	78	83	5
6	78	83	5
7	78	83	5
8	78	83	5
9	78	83	5
10	78	83	5
Station_5_reconstructed_layout			
1	6	11	5
2	53	59	6
3	67	73	6
4	80	85	5
5	92	97	5
6	104	109	5
7	126	132	6
8	139	145	6
9	151	157	6
10	194	199	5
Station_5_relocated_grease_pot			
1	32	36	4
2	44	49	5
3	57	61	4
4	67	71	4
5	78	82	4
6	88	92	4
7	98	102	4
8	108	114	6
9	121	126	5
10	212	216	4



Comparison time required	Original op	Reconstruc	Relocated grease pot
1	5	5	4
2	5	6	5
3	5	6	4
4	5	5	4
5	5	5	4
6	5	5	4
7	5	6	4
8	5	6	6
9	5	6	5
10	5	5	4
Average	**5**	**5.5**	**4.4**
Standard deviation		0.527046	0.699206
Median		5.5	4

t-Test: Two-Sample Assuming Unequal Variances

	Reconstructed assembly situation	*Relocated grease pot*
Mean	5.5	4.4
Variance	0.277777778	0.488888889
Observations	10	10
Hypothesized Mean Difference	0	
df	17	
t Stat	3.972733152	
P(T<=t) one-tail	0.000491823	
t Critical one-tail	1.739606726	
P(T<=t) two-tail	0.000983646	
t Critical two-tail	2.109815578	

Video footage	Number	End time	Action	Movement description	Requirements	
Assembly line video	5.1	1	Turn to grab bolt	Grab bolt from bin after turning to move from assembly location to material location.	R2.1	Assemblers must not be required to turn to pick up materials.
	5.2	1	Grab bolt	Grab the bolt.	-	-
	5.3	3	Reach to grease bolt	Grease bolt after reorienting the material and extending right arm to apply grease to bolt.	R1.1	Parts must not require preparation at the assembly line.
					R2.3	Assemblers must not be required to reorient materials.
	5.4	5	Turn to orient bolt in luggage carrier	Orient bolt in luggage carrier after lifting the luggage carrier and turning to inbetween material location and assembly location.	R2.4	Assemblers must not be required to lift materials.
					R1.6	Parts must be oriented in one motion to their assembly positions by the assembler.
					R2.1	Assemblers must not be required to turn to pick up materials.
Reconstructed assembly situation	5.a	1	Grab bolt after turning.	Grab bolt after turning.	R2.1	Assemblers must not be required to turn to pick up materials.
	5.b	3	Grease bolt.	Place bolt in grease pot after performing one step and reaching.	R2.27	Assemblers must not be required to perform steps.
					R1.1	Parts must not require preparation at the assembly line.
					R2.2	Assemblers must not be required to reach for materials.
	5.c	4	Lift luggage carrier.	Lift the luggage carrier with the left hand.	R2.4	Assemblers must not be required to lift materials.
	5.d	6	Push bolt in luggage carrier.	Push bolt in luggage carrier after turning the luggage carrier.	R2.1	Assemblers must not be required to turn to pick up materials.
Relocated grease pot	5.e	1	Grab bolt after turning.	Grab bolt after turning.	R2.1	Assemblers must not be required to turn to pick up materials.
	5.f	1	Grease bolt.	Place bolt in grease pot	R1.1	Parts must not require preparation at the assembly line.
	5.g	2	Lift luggage carrier.	Lift the luggage carrier with the left hand.	R2.4	Assemblers must not be required to lift materials.
	5.h	4	Push bolt in luggage carrier.	Push bolt in luggage carrier after turning the luggage carrier.	R2.1	Assemblers must not be required to turn to pick up materials.