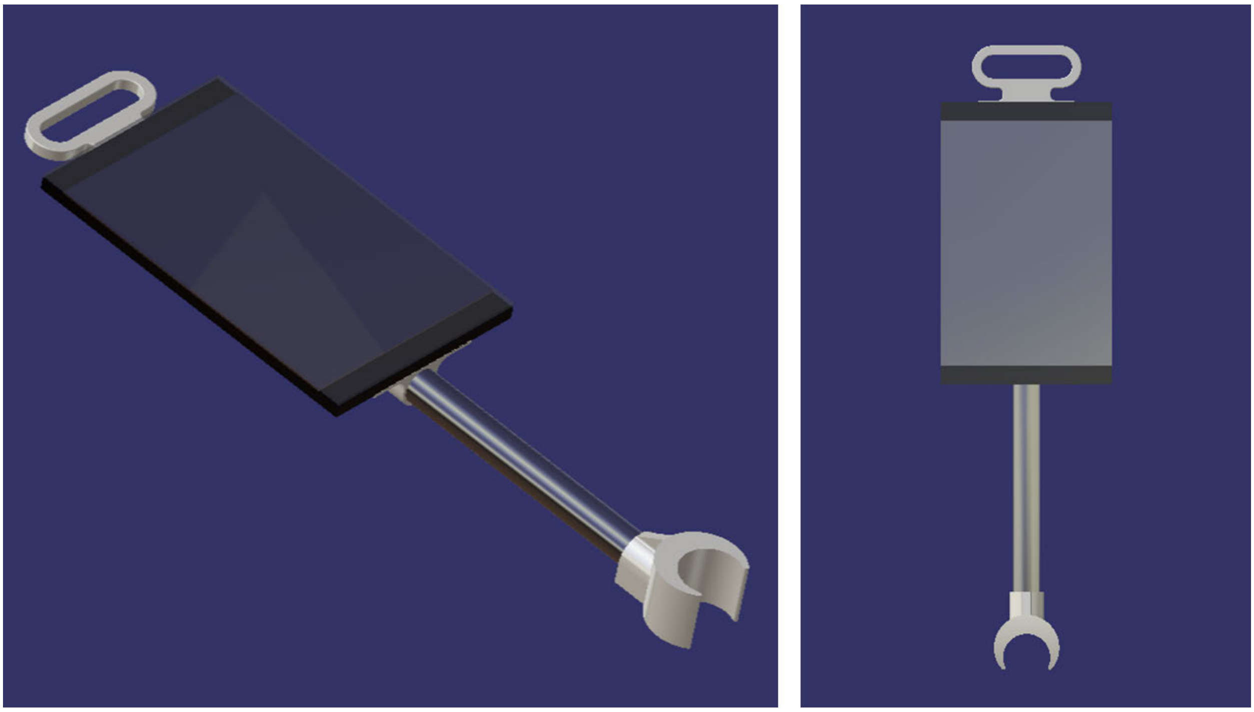

Design of a Solution for Blind Assembly of Bolts

Assembly of Low-visibility Bumper Bolts with a Focus on Ergonomics and Safety

Master's thesis in Product Development

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CHALMERS UNIVERSITY OF TECHNOLOGY
Gothenburg, Sweden 2025
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Abstract

This project focuses on the assembly of low-visibility bumper bolts under the truck model known as the Volvo FML- a process currently not possible on the assembly line due to challenging posture and safety hazards. The project seeks to solve these challenges, and ultimately allow Volvo Trucks in Tuve to shift this assembly from an after-line area where it is done presently, to the main line.

A linear product development methodology has been used with iterative test-design-build cycles inspired by lean principles. This was chosen over a more flexible, agile methodology to make it easier to coordinate activities with Volvo. A thorough pre-study was conducted to lay the theoretical groundwork for the project, which included both researching existing solutions to similar problems, and a detailed study of the current state. The current state analysis was then used to add detail to the problem statement. Key stakeholders were identified and continually contacted throughout the project to ensure the fulfilment of their interests in the project's outcome. Concept generation was conducted, which yielded 14 unique concepts in different phases of the project, while keeping the solution space as open as possible. Importance was placed on thoroughly documenting concept generation for Volvo's future reference. Selection and elimination matrices were used to refine or identify the best performing concepts in the initial stages, which yielded 3 concepts to prototype. The 3 prototypes were developed, and further elimination to obtain the winning concept was conducted at the last possible stage, only when feasibility or suitability was deemed impossible.

User testing and verification was conducted, which revealed the winning concept and resulted in 4 design changes to it. Well-researched ergonomics and safety testing methodologies were employed to verify suitability of the suggested solution. The final solution was tested on the moving assembly line, on the Volvo FML. One crucial trade-off was made, in the interest of ease of maintenance. Other suitable solutions have been suggested, with clear reasoning behind why they were not developed. The final solution solves the problem that has been proposed by Volvo.

Keywords: Ergonomics, Safety, Blind assembly, Under-up screws, Product Development, Assembly line

Acknowledgements

We would like to start by thanking Carl Reinhardt, the production engineer directly responsible for our thesis. He was always present, always happy to help, and went out of his way to find sources or information pertinent to the project.

We would like to thank Cecilia Berlin, our supervisor and examiner. She provided information critical to project structure, planning, and human factor resources such as ergonomics. Our limited background with ergonomics was not a major deterrent due to the abundance of support and resources provided by her.

At Volvo, support regarding work environment and ergonomics was also provided by Elin Algurén and Michael Schröder. They were easy to reach out to and very open to discussion, even about company-established methods.

Rapid prototyping was possible thanks to the cooperation and genuine excitement of Håkan Enesten and Aksel Möst at Lean Lab Tuve. They provided not only the material, tools, and the space to build prototypes, but also trained us in the usage of power tools or volunteered their time to do it for us.

We would like to thank the project manager Mikael Granbom. Apart from seeing an opportunity for a thesis in this problem, he ensured that we had a good space to work, provided us with critical IT resources, and kept an open line of communication in case of larger requirements from Volvo. He was also responsible for shedding light on a technology we did not know about during the concept phase of the project.

Finally, we would like to thank all the personnel at Tuve and within the Volvo Group. Our project, especially during the pre-study, made us reach out to several people throughout the organisation. We were always met with patience and kindness. Most of the people at Volvo answered any and all questions patiently and redirected us to relevant persons if they were not able to.

Ranjan Manohar and Simon Tuvestad, Gothenburg, June 2025

List of Acronyms

Below is the list of acronyms that have been used throughout this thesis listed in alphabetical order:

AI	Artificial Intelligence
CHAI	Change Agent Infrastructure
FMEA	Failure Modes and Effects Analysis
FML	Front Medium Low entry
FUP	Front Underrun Protection
HARM	Hand Arm Risk-assessment Method
LLM	Large Language Model
MEC	Manufacturing Ergonomics Checklist
PC	Polycarbonate
PETG	Polyethylene Terephthalate Glycol
REBA	Rapid Entire Body Assessment
RULA	Rapid Upper Limb Assessment

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1

Introduction

Volvo Trucks in Tuve produces a wide range of trucks to suit many market segments and customer needs. Their line of electric trucks includes the Volvo FML (Front Medium Low Entry) whose novelty poses some challenges on the assembly line.

1.1 Background

The Volvo FML is equipped with a low cabin to improve accessibility to the driver for applications that require frequent ingress and egress. Moving the cab lower resulted in a design change. This has come with the trade-off of having to assemble some of the mounting bolts of the front bumper from underneath the truck. A picture of the bolts' placement has been presented in figure 1.1.

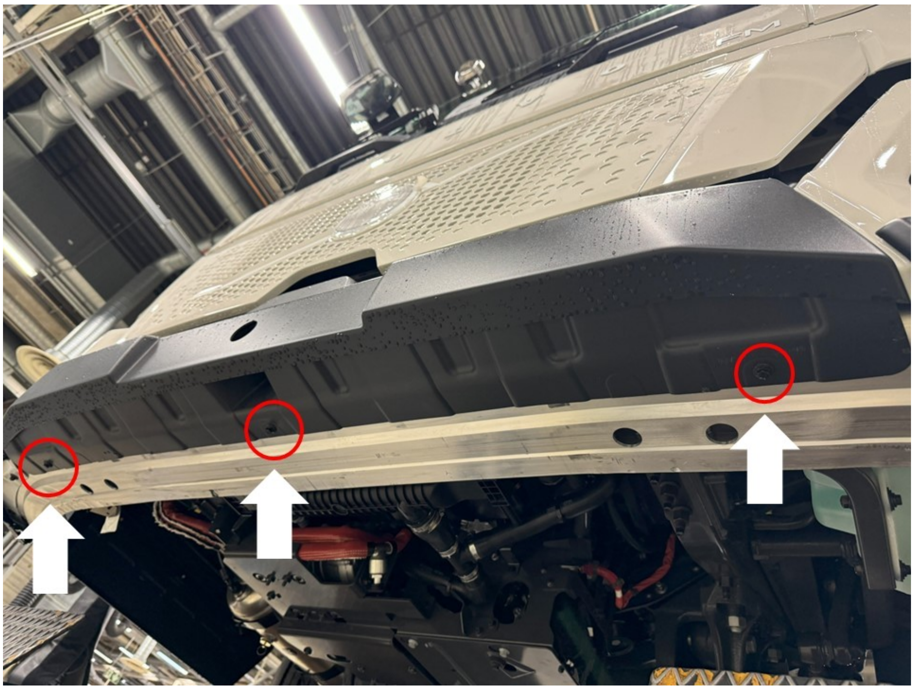


Figure 1.1: Bolts of interest under the Volvo FML's bumper

Presently, the truck is taken to the "adjustment department" at the end of the main assembly line with the bumper semi-assembled. This area is intended to repair trucks that have encountered problems on the main line. It is then raised on a jack and assembly is performed with the help of a battery-powered wrench. The present solution and the tool used have been presented in figure 1.2 and figure 1.3 respectively.

Figure 1.2: The Volvo FML raised with the help of a jack

Figure 1.3: Battery-powered torque wrench presently used for fastening

Fig. 1.4 shows how an operator on the production line would assemble the bolts today if it were carried out on the line. However, this is not in compliance with Volvo's internal requirements for workplace ergonomics and safety. The operator is forced to assume an uncomfortable posture and position themselves on the moving assembly line, wherein the truck being assembled moves towards them. [1]

This process of moving the truck to the adjustment area also wastes time and poses other safety risks, that could be avoided by performing the assembly in the intended area. It adds critical assembly work to the operators of an area who are meant for solving production errors, while potentially wasting the time of operators or stations that are intended to perform the assembly. For Volvo Trucks, this poses a risk of injury to its operators which could result in delays or interruptions. No prior work has been carried out to resolve this problem to the best of the project team's knowledge.

1.2 Aim

The aim of this project is to design a solution for the complete assembly of the bumper on the production line while complying with ergonomics and safety guidelines. The project aims to systematically explore the whole solution space before

Figure 1.4: Posture required for assembly of the bumper on the current assembly line, if no equipment were used

suggesting the final proposal.

The Technology Readiness Level rating system from NASA can be considered and adapted to set a goal for how ready the tool must be at the end of the project. [2] TRL 7 will be targeted, which in the context of this project will mean a fully-functional prototype that is briefly tested in the assembly environment. Higher levels require extensive testing and validation. The Gantt chart in Section 1.5 suggests that there might not be enough time to do a satisfactory amount of validation for higher TRL levels.

1.3 Limitations

These limitations address which parts of the problem the project will not be addressing. It is to set a scope and define the focus of the project.

1. While the proposed solution will be as general as possible so as to boost compatibility across trucks, it will not specifically address any truck other than the current model of the FML.
2. The focus of the project will remain the screws under the bumper of the FML and will not address any other fasteners that may have a similar visibility problem.
3. The future solution will be open to using the current fixtures and tooling on

the assembly line at the Tuve factory. Therefore, it may be limited to this manufacturing facility only.

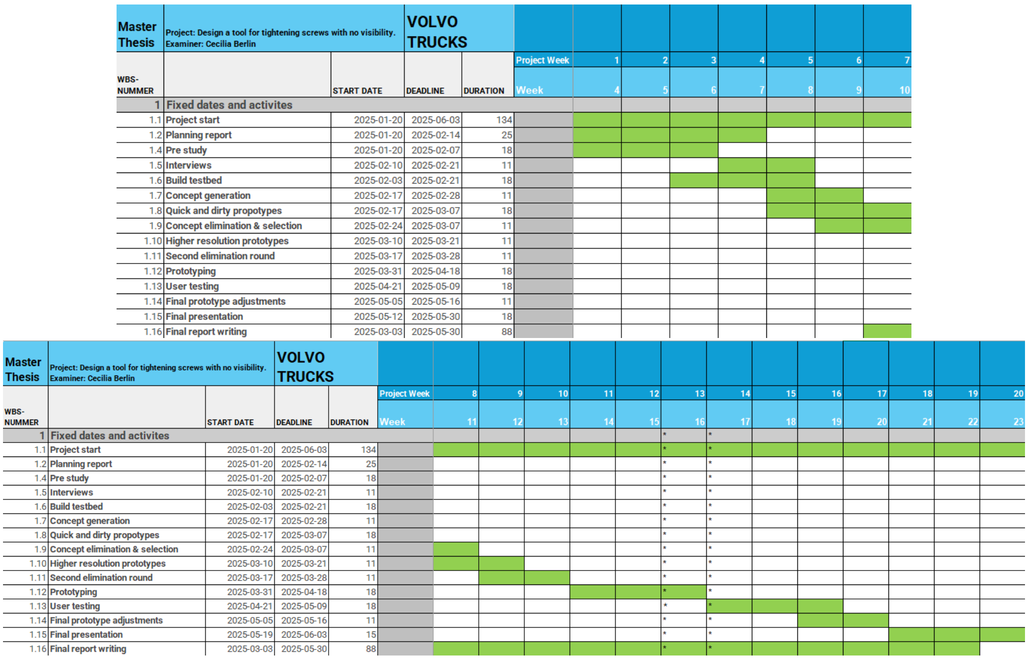
1.4 Research questions

A set of research questions have been set after some assembly line observations and a brief pre-study.

1. What requirements are placed on the solution for it to be useful in the assembly environment?
2. How can good ergonomics be ensured for the intended purpose?
3. What changes are required to the system/process, and by which stakeholders, to ensure usefulness and usage of the tool?
4. Who is affected by this project? How does it add value to these individuals?

1.5 Schedule

A Gantt chart was used to allocate time to different parts of the project as shown in fig. 1.5. It was updated continually according to the state of the project and any changing requirements. As each phase of the project drew closer, more detail was added to the chart to ensure fulfilment of deadlines. A list of key dates were outlined to ensure keeping up deadlines. These dates have been highlighted below in table 1.1.



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					Project Week	1	2	3	4	5	6	7
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1.2	Planning report	2025-01-20	2025-02-14	25		🟩	🟩	🟩	🟩			
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1.6	Build testbed	2025-02-03	2025-02-21	18				🟩	🟩	🟩		
1.7	Concept generation	2025-02-17	2025-02-28	11						🟩	🟩	
1.8	Quick and dirty propotypes	2025-02-17	2025-03-07	18						🟩	🟩	🟩
1.9	Concept elimination & selection	2025-02-24	2025-03-07	11							🟩	🟩
1.10	Higher resolution prototypes	2025-03-10	2025-03-21	11								
1.11	Second elimination round	2025-03-17	2025-03-28	11								
1.12	Prototyping	2025-03-31	2025-04-18	18								
1.13	User testing	2025-04-21	2025-05-09	18								
1.14	Final prototype adjustments	2025-05-05	2025-05-16	11								
1.15	Final presentation	2025-05-12	2025-05-30	18								
1.16	Final report writing	2025-03-03	2025-05-30	88								🟩

Master Thesis	Project: Design a tool for tightening screws with no visibility. Examiner: Cecilia Berlin		VOLVO TRUCKS																	
					Project Week	8	9	10	11	12	13	14	15	16	17	18	19	20
WBS-NUMMER		START DATE	DEADLINE	DURATION	Week	11	12	13	14	15	16	17	18	19	20	21	22	23
1	Fixed dates and activites										*	*						
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1.5	Interviews	2025-02-10	2025-02-21	11							*	*						
1.6	Build testbed	2025-02-03	2025-02-21	18							*	*						
1.7	Concept generation	2025-02-17	2025-02-28	11							*	*						
1.8	Quick and dirty propotypes	2025-02-17	2025-03-07	18							*	*						
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1.15	Final presentation	2025-05-19	2025-06-03	15							*	*				🟩	🟩	🟩
1.16	Final report writing	2025-03-03	2025-05-30	88		🟩	🟩	🟩	🟩	🟩	🟩 *	🟩 *	🟩	🟩	🟩	🟩	🟩	

Figure 1.5: Gantt chart for time allocation of the project

Event	Date
Submission of planning report-Work card	2025-02-14
Test rig completion	2025-02-21
Poster Presentation at Volvo	2025-05-14
Sharing of final report with opponent	2025-05-23
Presentation 1-Work Card	2025-06-03
Presentation 2-Work Card	2025-06-03
Presentation Opponent-Work Card	2025-06-04
Final Presentation-Chalmers	2025-06-03
Final Presentation-Volvo	2025-06-13

Table 1.1: Key dates during the thesis

2

Methodology

The project followed the structure as outlined in fig. 2.1. The project consisted of 4 major phases- Pre-study, Concept stage, Prototyping, and Testing, which were further divided into the key methods as described in the following sections.

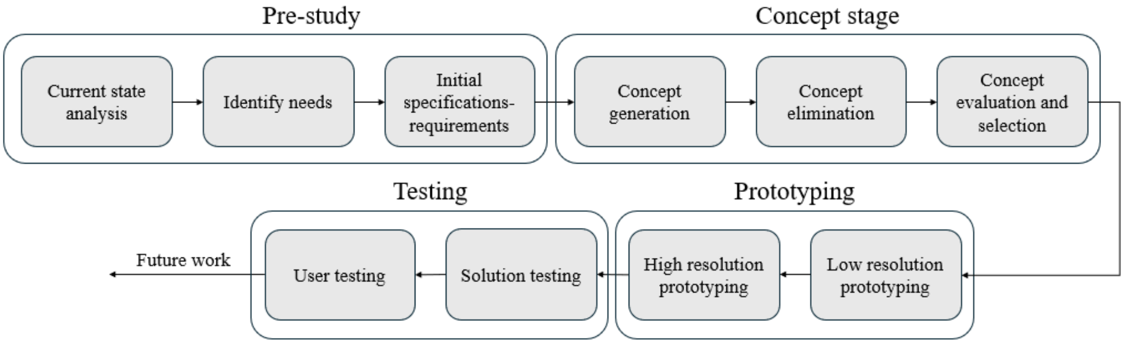


Figure 2.1: The project structure. A combination of the general concept development structure and the spiral product development process as proposed by Ulrich et. al. [3]

2.1 Pre-study

The pre-study was designed to address the following questions:

1. How can the different phases of the project be organised into the available time?
2. How can the problem be defined?
3. What are some of the limitations or the aspects of the projects the team will not be addressing?
4. What are some constraints that limit the scope of the project?
5. How can the project team explore the entire solution space?

2.1.1 Current state

During the Current state analysis, the assembly process was analysed with regard to ergonomics, safety, cost, time and other aspects. A thorough analysis was conducted for ergonomics and safety as these were the focus areas of the project. Photos and videos were used to conduct the analysis by applying the evaluation process described below. An understanding of the root cause of the problem was also gained. This was done to not only catch any oversights, but to also make it easier to contact relevant stakeholders later in the project.

Since ergonomics play a key part in this project, several methods from Production Ergonomics were considered [4]. Rapid Entire Body Assessment (REBA) analysis was chosen as it encompasses the full body and is not limited to the upper body like RULA (Rapid Upper Limb Assessment) or HARM (Hand Arm Risk-assessment Method). It analyses posture, which is important as there is expected to be little lifting in the prescribed task [5].

Key Indicator Method: Awkward Body Postures (KIM: ABP) was also considered as a complement to the REBA analysis [6]. However, new information was provided by Volvo about their proprietary ergonomics checklist. The "Manufacturing Ergonomic Checklist (MEC) worksheet", enclosed in Appendix C, was evaluated and found to include all aspects necessary. It was also easier to apply, interpret, and aligned with Volvo's standards. The only aspect missing from MEC was an evaluation method for the legs, since the worksheet only includes leg positions that are not permitted or restricted. To compensate for this, and to analyse posture more thoroughly, REBA analysis was also conducted.

Safety was also a key issue that was kept in focus during the project. For this purpose, two tools were used.

1. Failure modes and effects analysis (FMEA), for which the template provided by the Institute of Healthcare Improvement was used. [7]
2. Volvo's internal risk assessment process.

The Volvo risk assessment worksheet was missing two criteria from this FMEA analysis template:

1. "Failure causes"- the reason why a failure might occur.
2. "Likelihood of Detection"- the probability of an event going unnoticed.

"Failure causes" was added to the worksheet to ensure the analysis of the possible reasons why an unsafe event might occur. However, the "Likelihood of Detection" was omitted, as the project involves fairly simple processes where risks going unnoticed is not a major concern.

2.1.2 Problem Decomposition

The problem decomposition intended to break down the problem into smaller pieces so that each sub-problem could be approached independently before combining them in as many ways as possible using the morphological matrix [3]. This was done by means of a tree diagram [8]. This would also encourage the project team to think about as many solutions as possible.

2.1.3 Stakeholder analysis

A stakeholder has been defined as *"A person, group or organization that has interest or concern in a situation/organisation, etc."* and *"Someone who is involved in and/or affected by the course of action"* [9]. This can be interpreted as someone who influences or is influenced by the project. Therefore, "Key stakeholder" can be understood as a person or a group of persons who influences the project in a significant way.

A method was required to identify these key stakeholders. This was important to ensure the alignment of project goals with expectations. It also simplified communication during solution verification and testing, as these stakeholders were consulted frequently. Two questions were framed to assist with the identification of key stakeholders. Negative statements were used to make the evaluation process easier and more clear-cut.

- If the project were to be unsuccessful, will the stakeholder be impacted in a significant way?
- If the stakeholder were not to be involved, would the project be majorly disadvantaged?

The CHAI or Change Agent Infrastructure analysis was used to identify stakeholders [10]. Each role's description was understood by the project team after which possible actors were recognised.

2.1.4 Interviews and Information search

Interviews were set up with as many stakeholders as possible, who were identified through the stakeholder analysis. An information search was conducted which included using common search engines like Google, together with patent landscaping. This was done early in the project to understand if there was an existing solution that could be referenced or modified. Quantitative data collection methods like surveys were deemed unsuitable for this project. This was because the solution impacts only a limited number of people which would limit interest in the project and result in very few responses, providing very little usable data to draw any patterns from.

2.1.5 Initial Specifications

Using the data from interviews, a KJ analysis [11] was conducted to recognise categories of needs [8]. Then a needs list was formulated and importance was set for each need. Using the needs and constraints set by key stakeholders, a set of target specifications were formulated [3].

2.2 Concept stage

The problem decomposition was useful for brainstorming within the project group to find sub-solutions. Different sub-solutions were combined using a morphological matrix to generate many concepts. The morphological matrices forced the project team to generate creative solutions as all combinations were not simple. In order to explore the solution space thoroughly, a second information search including patent landscaping was conducted. This information was also added to the first information search sheet. Meetings were set up with other thesis groups both within Volvo Tuve and outside the organisation.

After the morphological matrix was formulated, the concepts were screened for feasibility and relevance. An elimination matrix was used to remove infeasible solutions in the concept elimination stage. Concept selection matrices were then constructed to first evaluate the concepts against one another, and then to select the best performing concept [3]. Fast or "quick and dirty" prototypes were made in parallel with the concept selection process wherever necessary and possible.

2.3 Prototyping

This phase followed the "Test-Design-Build" approach from the MPP126 course [12]. This approach emphasises testing a potential solution to evaluate feasibility early before putting in time to develop it further through detailed design. It is in contrast to the "Design-Build-Test" approach. Quick and dirty prototypes were made to assist with concept elimination and selection. Higher resolution prototypes were made for user testing and evaluation with key stakeholders. Towards the end of the project, high resolution prototypes were used in combination with selection matrices to evaluate between the final concepts.

2.4 Testing

The testing of prototypes consisted of solution testing and user testing. The solution testing sub-phase evaluated whether the solution fulfilled the intended purpose. This involved ergonomics and safety testing using the methodologies defined above, and ensuring that the demands set by the target specifications were met. This phase was conducted by the project team.

The user testing was conducted using the *"Concept Testing"* methodology defined by Ulrich et al. [3]. It was modified to suit project needs and the following steps were followed.

1. Purpose- defining the intent behind user testing, or defining research questions.
2. Survey population- means of sampling and selected users.
3. Survey format- how the interviews or surveys were conducted.

4. Concept communication means- selected method to show the survey population the solution under evaluation.
5. Measurement of user response- means of quantifying the response from the user.

User testing ensured the alignment of the solution with the project goals. It generated direct feedback from users and helped build a backlog of remaining work to bring the solution closer to deployment. The user tests consisted of a trial of the solution, an interview section and semantic scales. After the users performed the requested operation, they were asked to mark the semantic scales and the project team then conducted the interview, whose format can be seen in Appendix E.2. The semantic scales were designed to either understand the fulfilment of specifications set in 4.4 or to fulfil the purpose set for the user tests. The interview section sought to probe further into any extreme results and give an opportunity for the user to suggest changes or improvements. The concept, prototyping, and testing phases were iterative in nature and were often done in parallel.

2.4.1 Test bed

As the current state analysis highlighted, the Volvo FML's production is limited to 2 trucks a day. Therefore, a decision was made to build a test bed that would be representative of the conditions on the assembly line. The following goals were set for the test bed:

1. The test bed should be representative of the main assembly line as much as possible - it should simulate the height, parts of the truck, and any associated spatial constraints.
2. The test bed should serve as a means to test prototypes and potentially assist with user testing towards the end of the project.
3. The test bed should be easy to build and adjust so that any variations in assembly conditions are easy to simulate.

3

Current state

This chapter explores the processes and tooling that were used at the Volvo Tuve facility to perform the intended assembly prior to the project. It also explores the root cause of the issue, the ergonomics analysis of the present process, and a safety assessment.

3.1 Assembly line design

The Tuve facility has been designed to have a main assembly line to which several sub-assembly lines connect. The areas relevant to the project are as follows:

1. **FUP (Front Underrun Protection) sub-assembly line**- The sub-assembly line that connects to the main line at station 29. This line is responsible for the complete front of the truck such as the headlights and the bumper, but does not include the cab.
2. **Stations 29 through 43 or end-of-line**- The stations after the FUP sub-assembly line where a solution could potentially be implemented. Currently, the placement and partial assembly of the bumper is being done in station 36.
3. **Adjustment area or Part 11**- The area after the moving assembly line ends, where the assembly of the bottom bumper fasteners is currently taking place.

The assembly of the bumper must normally be done in the FUP sub-assembly area for all trucks. However, this is not possible for the FML.

3.2 The problem

After observation and documentation of the process of the FML on the production line, some additional limitations came to light for the project team. The FML is the only model that requires 6 fasteners to mount the FUP sub-assembly onto the chassis, with the other trucks requiring only 4. One major limitation is that it is not possible to assemble the bumper in the FUP sub-assembly area since it will hinder access to the additional two holes for the FUP bolts that are tightened at station 29, see fig. 3.1.

Since this assembly cannot be performed on the main line, Volvo Trucks has encountered instances where this process has been forgotten and the incomplete product

Figure 3.1: Additional bolts of the FUP concealed by the bumper for the FML

has been shipped to the customer. This has resulted in claims from the customer which have been expensive to address and rectify.

3.3 Root cause

After interviews with several stakeholders, the cause of the problem was identified. Due to a miscommunication during production development, the problematic location of the bumper screws was not identified by the production engineers and the designers until the pilot production of the truck. By this stage, a redesign was deemed too expensive and too time-consuming. A decision was made to retain the design and address the problem during production. This decision was also supported by the production volume of the FML, which was a maximum of 2 trucks a day.

3.4 Ergonomics assessment

The ergonomics assessment was conducted using MEC and REBA analyses as mentioned in Chapter 2. The assessment was conducted for the process presently used in the adjustment area, and also if the process were to be hypothetically carried out on the assembly line.

Figure 3.2: The assumed posture for the current solution

3.4.1 Adjustment

Due to the rarity of the FML, the process of assembly could not be documented. However, the process was simulated by the project team and an assessment was conducted. The posture of note has been indicated in fig. 3.2. The REBA analysis shown in Appendix C.1 reveals that the posture of the upper arm and the neck could be improved, and reports a score of 4 out of 15. The MEC does not uncover any issues, with a score of 13 out of 270 as shown in Appendix C.2.

The assembly process was performed by the project team on a truck that was not raised with the help of a jack. From this, the time taken to do the fastening process was noted, which was less than 10 seconds per fastener. Therefore, it was noted that the entire assembly process which comprises 3 fasteners can be completed within a minute, even accounting for changing postures and any minor operator errors.

The time noted above was important to assess the frequency section of the MEC. From Appendix C.2, it is apparent that the lowest frequency on the MEC aligns with this assembly operation across the checklist.

3.4.2 Main line

A video was taken during the assembly process and an ergonomics analysis was conducted on what the project team deemed were problematic postures. The postures were identified by noting extreme angles, loads far away from the body, and twisting of body parts. The postures have been highlighted in the fig. 3.3 and fig. 3.4. MEC reported a score of 40 out of 270 as shown in Appendix C.3 and REBA a score of 11 out of 15 as shown in Appendix C.4. While the MEC score seemed favourable, the REBA score of 11 out of 15 revealed that immediate action had to be taken if this theoretical process on the line were actually conducted. A closer look at the REBA analysis reveals that other than the wrist and lower arm, every other joint is in a non-ideal position. This clearly shows the need for the development of a new solution.

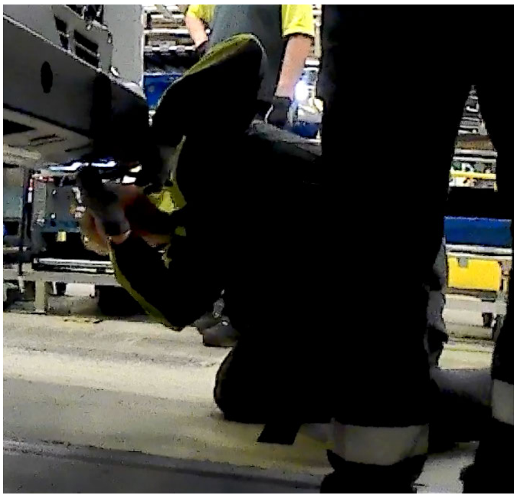


Figure 3.3: First problematic posture assumed during assembly on the line

Figure 3.4: Second problematic posture assumed during assembly on the line

3.4.3 Reflections

A meeting with the ergonomics expert at Volvo revealed that the positions assumed on the line were highly problematic and were not permitted as they would expose the operator to overload injuries. This meeting was a good verification method for the project team as it ensured that the evaluation method was applied as intended. The evaluation also exposed cases that the MEC does not screen well, which is postures with large angles of bending and twisting but with low frequency. In summary, a significant ergonomics benefit can be gained by introducing a new assembly process.

3.5 Risk assessment

A risk assessment was conducted for the assembly process in both the adjustment area and if the process were hypothetically conducted on the line. Each identified risk was given a score out of 25 obtained by multiplying the probability of occurrence with the severity of risk as shown in Appendix B.1. The assessment was conducted in collaboration with the safety officer of the assembly line with inputs from the production engineer responsible for the pertinent section of the line.

The assessment conducted for the current process in adjustment shown in Appendix B.2 reveals two events that risk very serious injury, which are "Tow truck could drive over operators" and "Truck is lowered with operators below". While these risks could be somewhat mitigated by using safety measures such as a siren on the truck or a safety check before lowering the hydraulic jack, they cannot be eliminated without a process change. Eliminating these risks is important as the consequences are severe.

In the assessment for the theoretical assembly on the main line shown in Appendix B.3, one possible event- "truck could knock down the operator"- could lead to very serious injury. This is indicated by the high score of 12 out of 25. However, the process itself is far from ideal as highlighted by the index scores. The process risks injuries due to posture, assembly position in front of the truck, and obstructions in the assembly area.

In both situations, possible events were identified which could lead to serious operator injury. While some concerns could be addressed with other measures, the more critical concerns could only be resolved by changing the process and moving it to the main assembly line. For example, the tow truck that carries the truck from the main line to adjustment when the truck is non-functional risks running over operators. This can be avoided or eliminated only by avoiding bringing the truck to adjustment. Similarly, a truck collapsing on the assembly line cannot be avoided. However, operators working under the truck can be prevented by using appropriate tools and equipment.

In conclusion, a significant reduction to risk can be achieved by introducing a new assembly process.

4

Pre-study

4.1 Problem decomposition

The project team verified four main tasks, which were *Position the screw, Position the tool, Fasten* and *Store*. The main tasks are broken down into sub-groups or sub-solutions, depending on the task. The task *Position the screw* is for example broken down into sub-tasks of *See the hole, Load screw and Align hole.* Further, the sub-task *Load screw* has the sub-solutions *In the tool, In the bumper* and *In the FUP*. The complete problem decomposition can be found as a tree diagram in fig. 4.1.

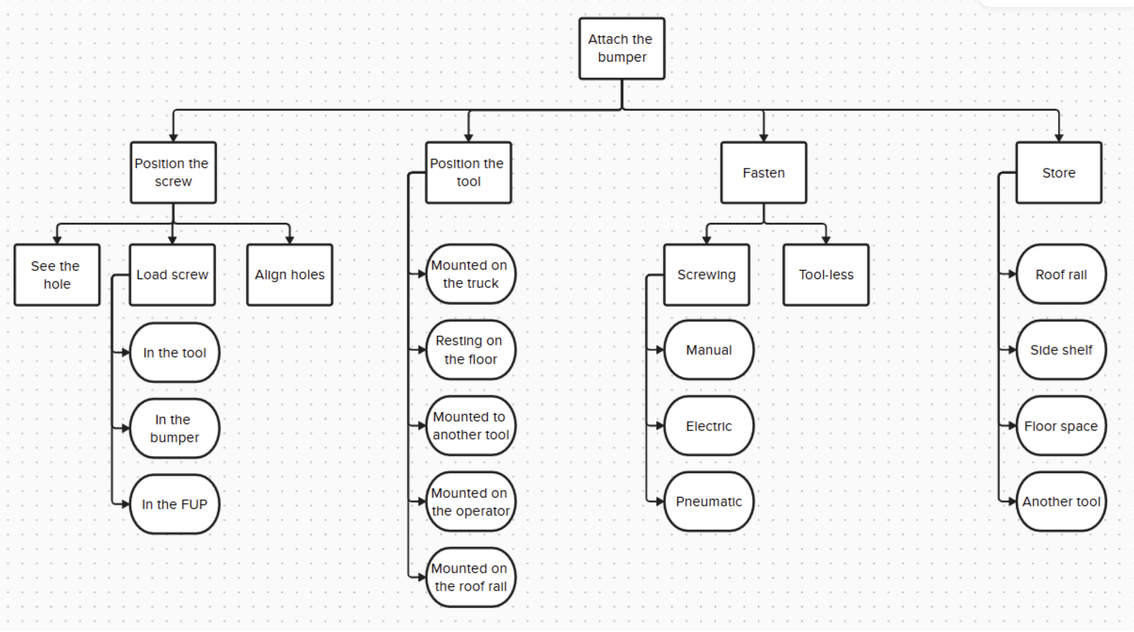


Figure 4.1: Problem decomposition using tree diagram

4.2 Stakeholder analysis

The stakeholder analysis identified 16 different stakeholders using CHAI methodology and comprised individuals or groups of individuals. Key stakeholders were then identified using the stated methodology. This was done to keep the people most influenced by the project in focus.

4.2.1 CHAI

The CHAI or Change Agent Infrastructure analysis method was used to systematically identify different stakeholders of the project as shown in fig. 4.2 [10]. Some changes were made to the analysis as the project progressed which have been documented as follows:

1. "Production engineer, end of line", although a production engineer, has been highlighted as this role is fulfilled by this project's supervisor at Volvo. He was responsible for the creation of the project and the other production engineers did not have a significant stake in the project which was recognised after interviews.

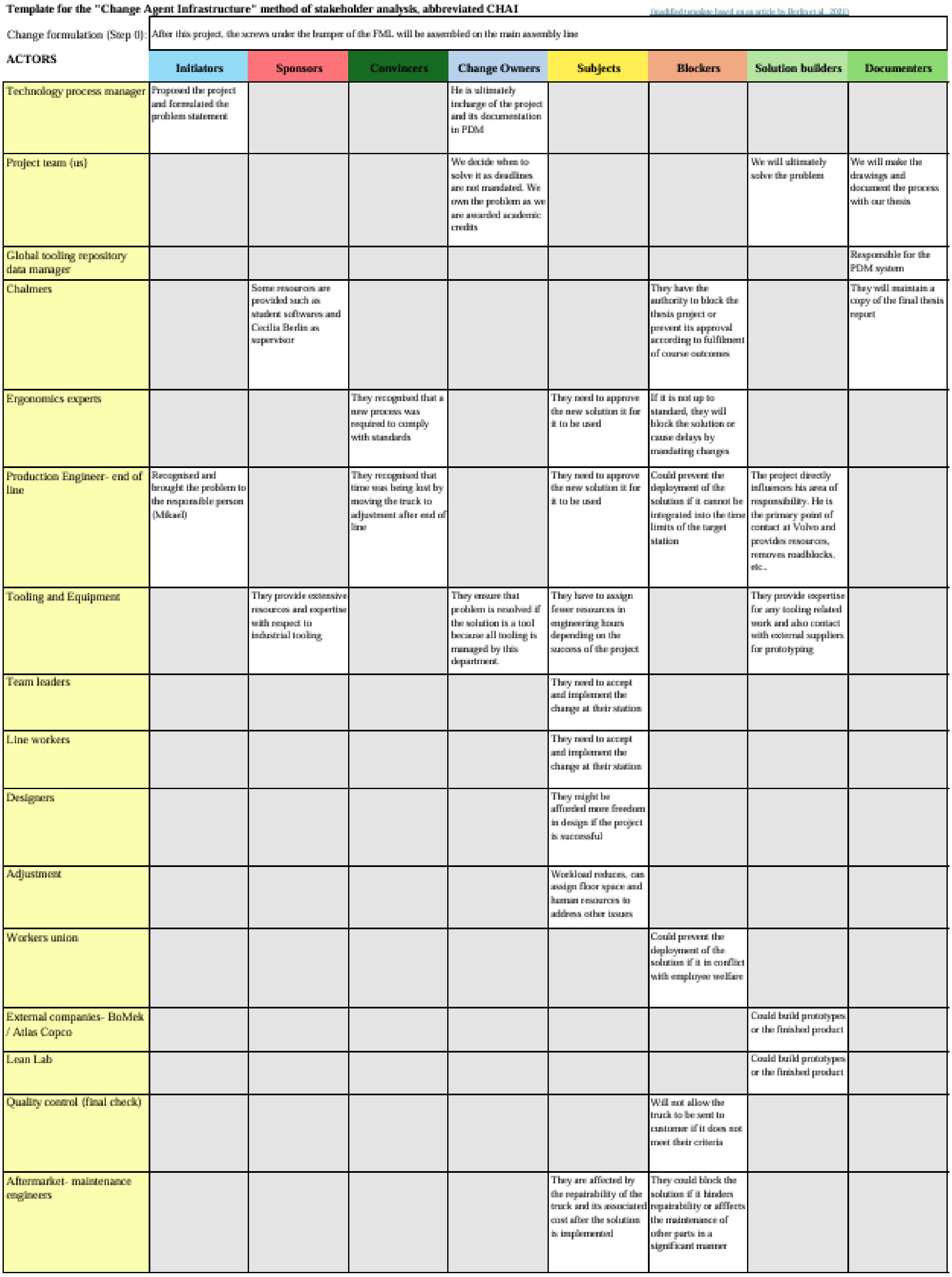
2. "Aftermarket" or "maintenance engineers" was added as an actor after the initial CHAI analysis and during the interview stage. This actor was recognised from the interviews conducted.

3. "Logistics" was a stakeholder that was removed after interviews as the department deals exclusively with the parts that are assembled onto the truck and not with the tooling or equipment used on the assembly line.

In the event of a block, the solution will be partly or wholly changed, as most of the recognised blocks stem from the suggested solution. A re-evaluation of all the generated concepts will be conducted and a new method will be implemented if time permits, with the new considerations in mind. "Chalmers" is the only blocker that does not pertain directly to the suggested solution. In this case, the supervisor Cecilia Berlin will be consulted to frame a plan of action.

4.2.2 Key stakeholders

The key stakeholders have been listed in table 4.1.



Template for the "Change Agent Infrastructure" method of stakeholder analysis, abbreviated CHAI

(modified template based on an article by Berlin et al., 2021)

Change formulation (Step 0): After this project, the screws under the bumper of the FML will be assembled on the main assembly line

ACTORS	**Initiators**	**Sponsors**	**Convincers**	**Change Owners**	**Subjects**	**Blockers**	**Solution builders**	**Documenters**
Technology process manager	Proposed the project and formulated the problem statement			He is ultimately incharge of the project and its documentation in PDM				
Project team (us)				We decide when to solve it as deadlines are not mandated. We own the problem as we are awarded academic credits			We will ultimately solve the problem	We will make the drawings and document the process with our thesis
Global tooling repository data manager								Responsible for the PDM system
Chalmers		Some resources are provided such as student softwares and Cecilia Berlin as supervisor				They have the authority to block the thesis project or prevent its approval according to fulfilment of course outcomes		They will maintain a copy of the final thesis report
Ergonomics experts			They recognised that a new process was required to comply with standards		They need to approve the new solution it for it to be used	If it is not up to standard, they will block the solution or cause delays by mandating changes		
Production Engineer- end of line	Recognised and brought the problem to the responsible person (Mikael)		They recognised that time was being lost by moving the truck to adjustment after end of line		They need to approve the new solution it for it to be used	Could prevent the deployment of the solution if it cannot be integrated into the time limits of the target station	The project directly influences his area of responsibility. He is the primary point of contact at Volvo and provides resources, removes roadblocks, etc..	
Tooling and Equipment		They provide extensive resources and expertise with respect to industrial tooling		They ensure that problem is resolved if the solution is a tool because all tooling is managed by this department.	They have to assign fewer resources in engineering hours depending on the success of the project		They provide expertise for any tooling related work and also contact with external suppliers for prototyping	
Team leaders					They need to accept and implement the change at their station			
Line workers					They need to accept and implement the change at their station			
Designers					They might be afforded more freedom in design if the project is successful			
Adjustment					Workload reduces, can assign floor space and human resources to address other issues			
Workers union						Could prevent the deployment of the solution if it in conflict with employee welfare		
External companies- BoMek / Atlas Copco							Could build prototypes or the finished product	
Lean Lab							Could build prototypes or the finished product	
Quality control (final check)						Will not allow the truck to be sent to customer if it does not meet their criteria		
Aftermarket- maintenance engineers					They are affected by the repairability of the truck and its associated cost after the solution is implemented	They could block the solution if it hinders repairability or affects the maintenance of other parts in a significant manner		

Figure 4.2: CHAI method for stakeholder analysis [10]

Stakeholder	Justification
Project Team	Responsible for the conduction of the project, set the scope for the project, and, to a limited extend, decide the schedule.
Production engineer, end of line	The proposed method will be implemented in his area of responsibility. He is also directly responsible as the project supervisor.
Ergonomics experts	They must deem the solution uses acceptable ergonomics for it to be used by Volvo Trucks.
Tooling and Equipment	Maintain the final drawings in the PDM system. Provide resources through expertise and designs of equipment in the factory.
Team leaders and assembly workers	The ultimate users of the solution.
Lean Lab Tuve (prototyping workshop)	Critical to most fast prototyping and testing conducted during the project. The test bed's complete construction was done using Lean Lab equipment.
Chalmers / examiner	Will ultimately approve the project and its outcomes.

Table 4.1: Key stakeholders with reasoning.

4.3 Mission statement

The mission statement can be found in table 4.2. Each section as suggested by Ulrich et al. was considered, discussed amongst the project group or with relevant stakeholders, and formalised into the table [3]. "Solution Description" was taken mainly from the problem statement as proposed by Volvo Trucks for example, while "Key stakeholders" was a result obtained from previous sections. Minor modifications were made to the format to suit this project's needs better. The mission statement did not include primary and secondary markets as this project aims to make a solution that will remain within Volvo. Limitations were appended with assumptions to clearly define the parts of the project that will consciously not be addressed.

4.4 Interviews

From the stakeholder analysis, specifically the CHAI-analysis, the team recognised key members to interview. The interviews acted as a deep dive into how the organization works and the responsibilities of each stakeholders. The most important stakeholder the team identified for this project were the assembly workers. However, interacting with them proved a challenge as they worked in shifts and had little time to spare for interviews.

Another important stakeholder for this project was the production engineer respon-

Solution description	New solution to assemble bolts under the bumper of the Volvo FML on the assembly line in the Tuve Plant
Benefit proposition	1. Faster customer delivery 2. Prevention of claim from customer due to missed assembly step 3. Safer assembly process 4. More ergonomic assembly process
Key goals	1. Usage of the solution for the assembly of bolts on the FML model in production 2. Complete solution by June 2025
Assumptions and limitations	1. Focus placed on the FML specifically and not other truck variants 2. Focus placed on the bolts under the bumper specifically 3. The solution will be designed for the Tuve factory 4. No budgetary constraints for a functioning solution 5. No design change to existing truck parts 6. Solution will not be fully-autonomous; it will require an operator to intervene
Key stakeholders	1. Project team 2. Production engineer, end of line- project supervisor 3. Ergonomists 4. Tooling and equipment 5. Team leaders and line workers 6. Lean lab, Tuve 7. Chalmers

Table 4.2: Mission statement inspired by Ulrich et al. [3].

sible for the current assembly procedure of the bumper bolts. They were also the team's supervisor at Volvo and the person who had identified the issue initially to make this thesis possible. It was important to understand why this was an issue and how they would prefer the problem to be solved. They would also be the first step in identifying any obvious constraints.

4.4.1 KJ-analysis

Key statements from interviews which expressed needs were noted from the recordings by the project team. The statements were kept as close to how the interviewee stated it as possible. These were then grouped into logical blocks as can be seen in fig. 4.3 using an online tool "Mural" (mural.co). These blocks were then labelled. The labelled blocks were condensed into a needs list.

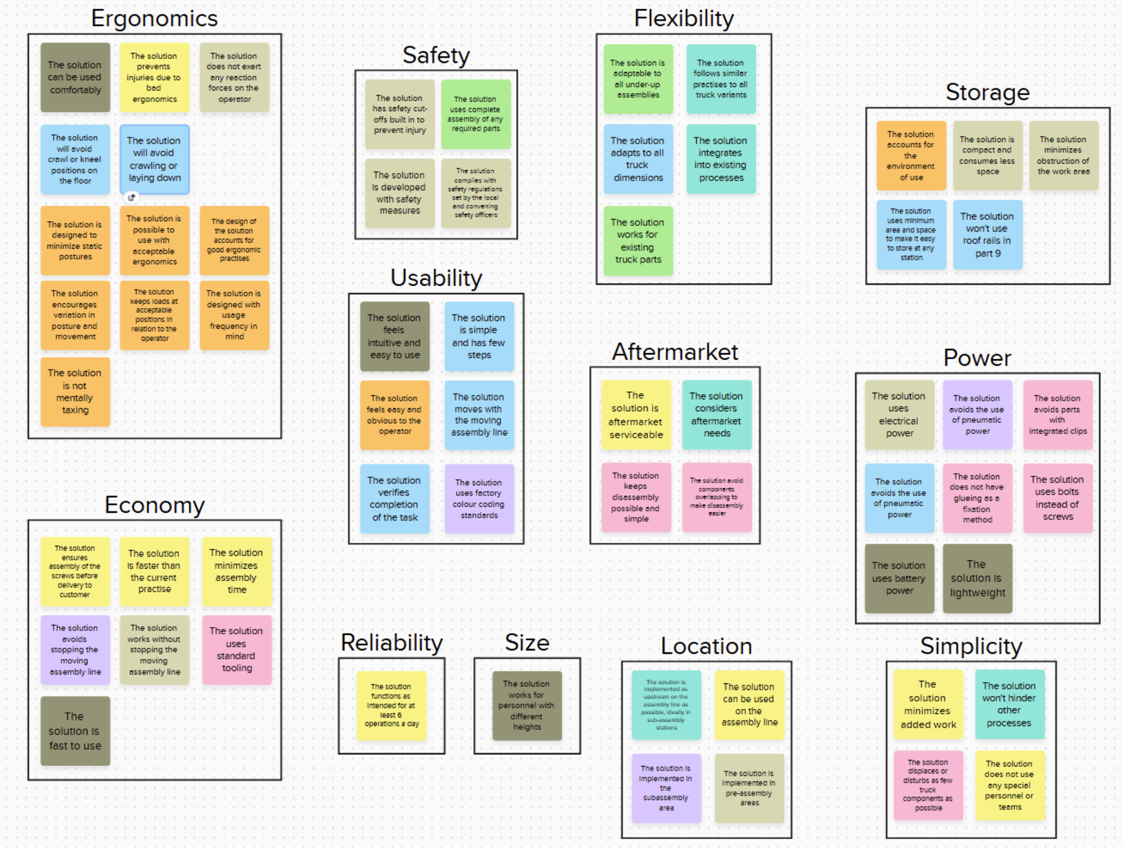


Figure 4.3: KJ analysis conducted from statements from interviews [8] [11]

4.4.2 Customer Needs

From the interviews with relevant stakeholders and the KJ analysis, a customer needs list was formulated. In the customer needs list, 12 different groups were verified with the help of the KJ-analysis, as seen in 4.3. "Sub-needs" were recognised in the need groups, to which ranks were assigned. The needs have a rating of (*) from

1-3, where 3 is the most important. Latent needs were denoted by an exclamation mark (!) [3].

1. The solution can be used with good ergonomics
    a) The solution places weights close to the body ***
    b) The solution avoids laying down or crawling ***
    c) The solution avoids static postures *
    d) The solution does not exert high forces on the operator *
    e) The solution is not mentally taxing *
    f) The solution is lightweight and comfortable to handle *
2. The solution is safe to use
    a) The solution has safety measures to prevent improper use **
    b) The solution complies with safety regulations ***
    c) The solution ensures complete assembly of all parts ***
3. The solution is easy to learn and use.
    a) The solution has few steps *
    b) The solution introduces few new processes **
    c) The solution uses standard tooling **
4. The solution is accessible.
    a) The solution is ambidextrous !**
    b) The solution can be used by individuals of all heights **
5. The solution is reliable.
6. The solution occupies minimum space **
7. The solution can be used on the assembly line
    a) The solution can be used on the main assembly line ***
    b) The solution is implemented as upstream on the assembly line as possible *
8. The solution is used when operator is static relative to the truck *
9. The solution uses factory colour coding standards **
10. The solution is fast **
11. The solution is adaptable to all under-up assemblies *
12. The solution allows for disassembly and service
    a) The solution avoids glueing ***
13. The solution avoids using pneumatic power ***

Table 4.3: Customer needs list

4.5 Initial Specifications

From the customer needs list the project team was able to make an initial target specification [3] for the solution as shown in table 4.4. Each specification has been linked to one or more needs from table 4.3. The requirement and desires (R/D) are to determine whether the specification is a requirement for the solution or a desire from the interviewed personnel at the Tuve factory. Weight (W) determines how important the desires are and which ones should take a larger focus. The requirements are not given a weight as they are expected to be fulfilled. The weights are determined on a rating scale from 1-5, where 5 is the most important. Marginal and ideal values were then assigned with respect to the verification method. These were target values for the team to quantify and verify specifications.

Further, some of the less obvious specifications will be explained in more detail below.

1. Perceived weight - is the complete weight of the final solution and the weight has been cross-referenced with Volvo's ergonomics guidelines [1].
2. Reaction force - The ideal value here is 0 N and the marginal value has been calculated by using the existing tool (24 Nm) at a distance of 0.3 m from the body. This is the ideal allowed ergonomic distance to hold something according to Volvo's ergonomics guidelines [1].
3. Two of the demands refer to a semantic scale. The semantic scales in these cases refer to a 1-5 scale where, for example, 1 is "Very mentally straining" and 5 is "Not mentally staining" for Sl.no 4.
4. The safety aspects of the solution will be verified by conducting a risk assessment. The Volvo internal risk assessment template will be used and enclosed in appendix. The assessment highlights the risk using a simple green, yellow, and red colouring system indicating low/no risk, medium risk, and high risk respectively.
5. An ideal value of 30 s and marginal of 120 s have been set for the assembly time values based on the time the truck spends at each station on the main line. The ideal value was set based on the minimum amount of time every relevant station had available and marginal according to the time most stations had available.
6. An assembly step was defined as any new operation done by the operator to perform or to aid in performing the fastening process.
7. A new tool was defined as any instrument or device that would perform the assembly process directly or indirectly. Ideally, 0 new tools should be added and the 90 degree torque wrench used in current practise must be maintained.
8. The height ranges have been selected from the anthropometric data provided in Volvo's ergonomics guidelines [1]. The ideal value encompasses 5th percentile Asian/Mexican women to 95th percentile European/American men. The marginal value encompasses 5th percentile to 95th percentile European/American women.
9. The Tuve plant can produce a maximum of two Volvo FMLs per day. This

means that the solution will have to be used a maximum of 6 times a day, as it is 3 fastening operations twice a day. Accounting for about 25% human error, a minimum of 8 operations will need to be performed per day. An ideal value of 100 has been set as a largely optimistic case.

4.6 Information search

The information search for this project was done by exploring the internet, patents and other sources for some inspiration of a possible solution.

By exploring websites with a large number of different products, the project team was able to take valuable inspiration to be able to generate solutions of broader variation. This was to make sure that the project team considered as solutions of all kinds. A few examples of the sites used were Amazon (amazon.se) and Biltema (biltema.se) for their wide variety of products. The product search can be found in Appendix A.2.

For the patent search, Google Patents (patents.google.com) and Espacenet (worldwide.espacenet.com) was used to make sure that the final solution does not infringe on any active patents, and also to try and gain inspiration. Some examples of search terms to locate specific patents used by the project team was, "*Remote socket wrench*", "*no-visibility tool*", "*blind assembly tool*" and "*socket wrench camera*". The patent search can be found in Appendix A.1.

The information search, both product and patent, was later expanded during the concept phase, with the same system and document being used.

Sl. no.	Need no.	Specification	R/D	W	Unit	Marginal value	Ideal value	Verification method
1	1a,1f	Perceived weight	D	4	kg	12	<3	Dynamometer
2	1d	Reaction force	D	2	N	7.2	0	Dynamometer
3	1b,1c	Posture	R	-	Colour	Yellow	Green	MEC, REBA
4	1e	Mental strain	D	1	Semantic scale	2	5	User testing
5	2a	Auto cut-off time	R	-	s	3	<1	Stopwatch, user testing
6	2a,2b,2c	Safe to use	R	-	Colour	Yellow	Green	Volvo Risk Assessment
7	3a,10	Assembly time	R	-	s	120	<30	Solution testing
8	3	Easy to use	D	3	Semantic scale	2	5	User testing
9	3a	No. of new assembly steps	D	2	Number	3	1	Observation
10	3c	No. of new tools	D	3	Number	3	0	Observation
11	4a	Ambidexterous	D	5	-	-	-	User testing
12	4b	Height	R	-	mm	1520-1829	1497-1989	Tape measure
13	5	Frequency of use	R	-	Ops per day	8	100	Solution testing
14	12a	Glue	R	-	-	-	No	Solution testing
15	13	Power source	R	-	-	Manual	Electric	-

Table 4.4: Initial specifications

5

Concept phase

This chapter will explore the different concept phases in this project. From generating ideas, eliminating infeasible concepts with screening processes, to finally evaluating the remaining concepts.

5.1 Concept generation

This section will cover the project team's concept generation results. It will cover brainstorming, the morphological matrix, and finally the concepts generated.

5.1.1 Brainstorming/idea generation

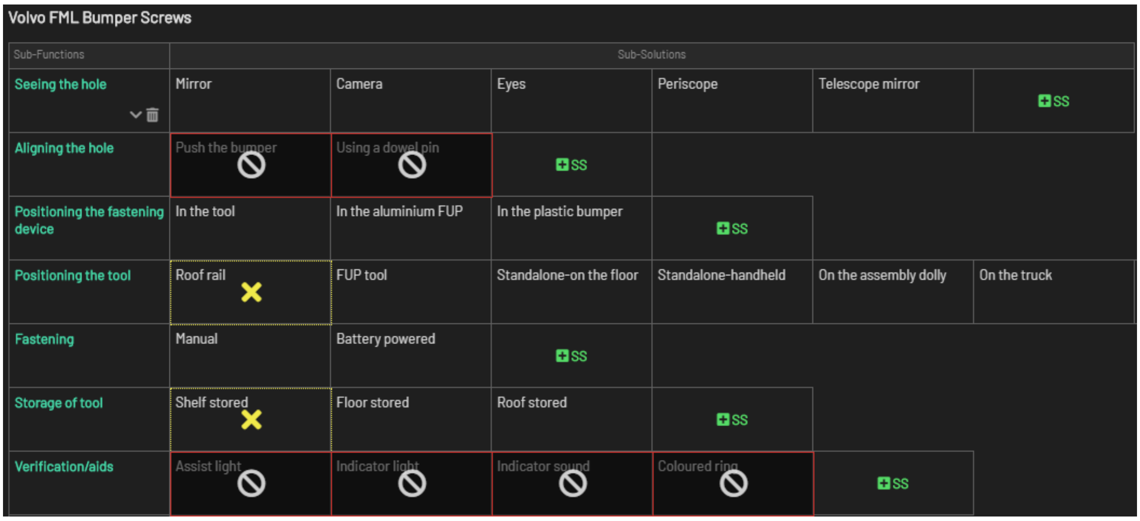
The idea generation for this project started with the project team exploring possible solutions on their own and then reuniting and discussing the ideas together. The idea generation process was mostly done using internet searches, together with our own knowledge of items and products that could be used as potential solutions. The collection of inspiration ideas can be found in Appendix A.

One of the idea generation sessions for this project took place together with another group at Volvo in Tuve. The idea behind this was to be able to get some input from people who are not involved in the project and therefore might have different views and solutions on how to solve the problem.

5.1.2 Morphological matrix

From the information gathered in the pre-study, the project team was able to construct a morphological matrix using the software *Morpheus* [13]. In the morphological matrix, 7 sub-functions were used from the tree diagram: *Seeing the holes. Aligning the hole*, *Position the fastening device*, *Position the tool*, *Fastening*, *Storage of tool* and *Verification/aids.*

The sub-solutions were inspired by the brainstorming/idea generation. However, some delimitations were added to the morphological matrix to minimize the number of generated concepts and to eliminate solutions that have non-compatible solutions. One example of incompatible sub-solutions is *Position the tool*: Roof rail and *Storage of tool*: Shelf stored which can be seen in fig. 5.1. In total, the project team recognised 16 incompatibilities.



Volvo FML Bumper Screws

Sub-Functions	Sub-Solutions					
Seeing the hole	Mirror	Camera	Eyes	Periscope	Telescope mirror	⊞SS
Aligning the hole	Push the bumper ⦸	Using a dowel pin ⦸	⊞SS			
Positioning the fastening device	In the tool	In the aluminium FUP	In the plastic bumper	⊞SS		
Positioning the tool	Roof rail ✗	FUP tool	Standalone-on the floor	Standalone-handheld	On the assembly dolly	On the truck
Fastening	Manual	Battery powered	⊞SS			
Storage of tool	Shelf stored ✗	Floor stored	Roof stored	⊞SS		
Verification/aids	Assist light ⦸	Indicator light ⦸	Indicator sound ⦸	Coloured ring ⦸	⊞SS	

Figure 5.1: Example of an incompatible sub-solution, denoted by yellow crosses

The team also added some blockers for sub-solutions and sub-functions to reduce the total number of solutions. In total 2 sub-function categories were blocked, *Aligning the hole* and *Verification/aids*. The thought behind this was that the sub-solutions in *Verification/aids* can be added to any solution as aids and does not depend on a single generated solution. For *Aligning the hole* the project team decided to generate separate dedicated concepts to solve the alignment issue.

The project team was able to narrow the morphological matrix down to 180 viable solutions which were then used to aid concept generation.

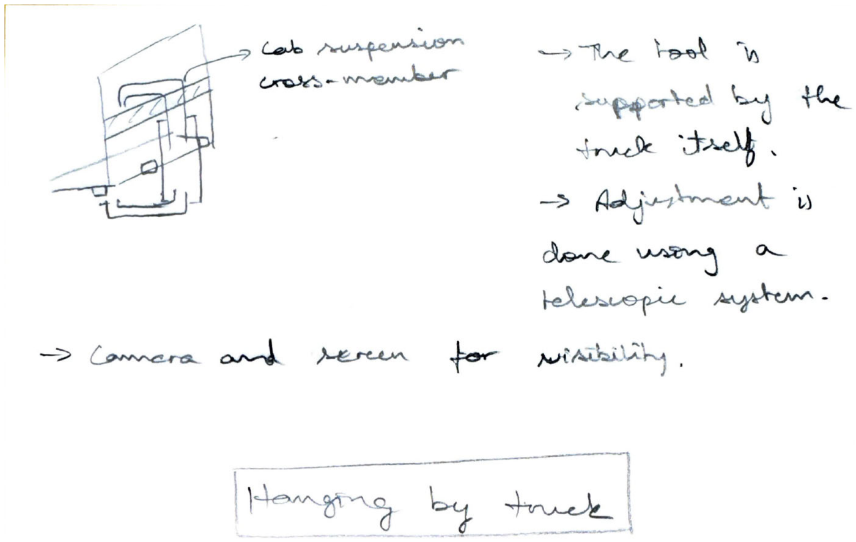
5.1.3 Generated concepts

From the brainstorming/idea generation sessions and some help from the morphological matrix, the project team was able to generate 9 different concepts and 3 alignment concepts. These concepts will be explained in more detail in the following section.

Concept 1 - Hanging by truck

As visualised in fig. 5.2, this solution hangs on the cab suspension cross-member at the front of the truck. The idea is that the solution can be shifted from side to side, with the suspension member as a guide, and the distance to the screws would be in marked locations so that the tool operator can easily perform the tightening sequence. The exact location of the screw and hole can be tracked on a screen that is located on the side of the tool.

The cab suspension cross-member is a beam that runs across the front of the cab connecting two coils that help the cab of the truck tilt forwards. This member is cylindrical and is easily accessible to the operator during the assembly process in the stations of interest on the line.



→ The tool is supported by the truck itself.

→ Adjustment is done using a telescopic system.

→ Camera and screen for visibility.

Figure 5.2: Concept 1 - Hanging by truck

Concept 2 - Metal detector

The second concept was inspired by the way metal detectors are held. The arm is supported either at the back of the upper arm or in the front, depending on the weight distribution of the other components. Some of the other components can be seen in fig. 5.3.

A clip-on handle could then make the tool ambidextrous based on the user. This handle could house the grip and trigger to force the tool's two handed usage, making it safer.

Concept 3 - Lift solution

This solution involved mounting the existing 90 degree torque wrench being used on the assembly line on a frame that can move on the ground and provide height adjust. The area can be visualised by using a camera mounted to either the frame or the tool itself. This is then complemented by a screen mounted to the handle.

A clip-on handle, like in the previous concept, could also be used here to the same benefit.

The solution has been illustrated in fig. 5.4.

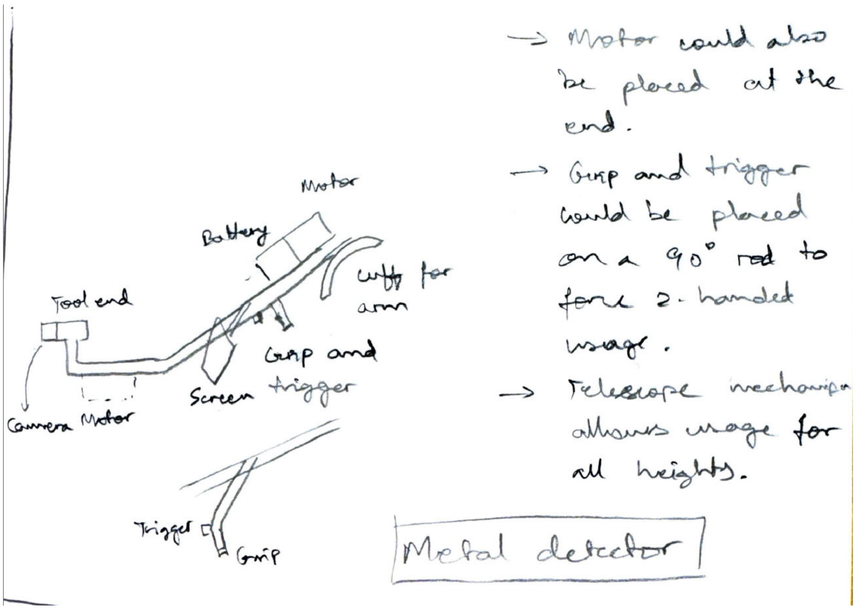


Figure 5.3: Concept 2 - Metal detector

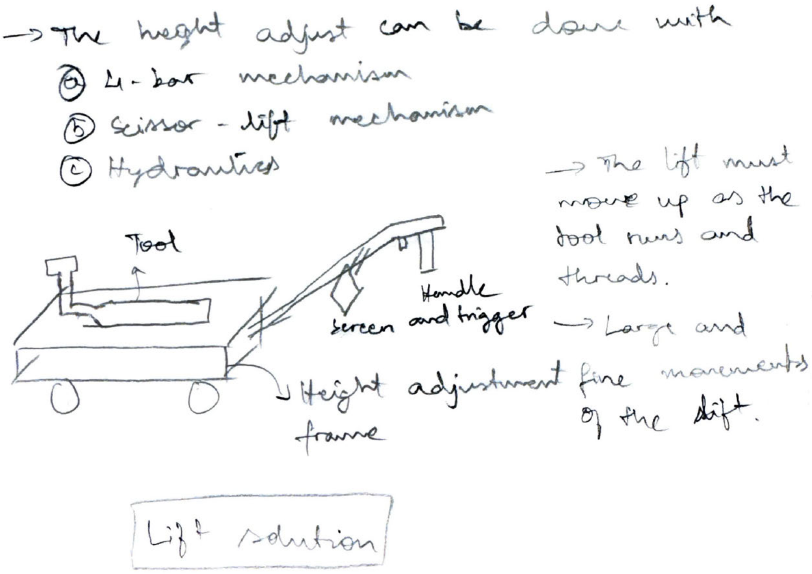


Figure 5.4: Concept 3 - Lift solution

Concept 4 - Tool+kneel

The main assembly line houses a chain drive that pulls the trucks under assembly at a constant speed. "Dollys" or modular wheeled carts can be mounted and dismounted at any time to this chain drive, which results in zero relative displacement between the moving truck and the cart.

A new dolly with padding can be designed to let the operator kneel comfortably and safely, as the risk of the truck moving over them is minimized. This can be combined with a simple mirror and an assist lamp to visualise the underside of the truck and help assembly. The standard 90 degree torque wrench can then be used safely. The solution has been illustrated in fig. 5.5.

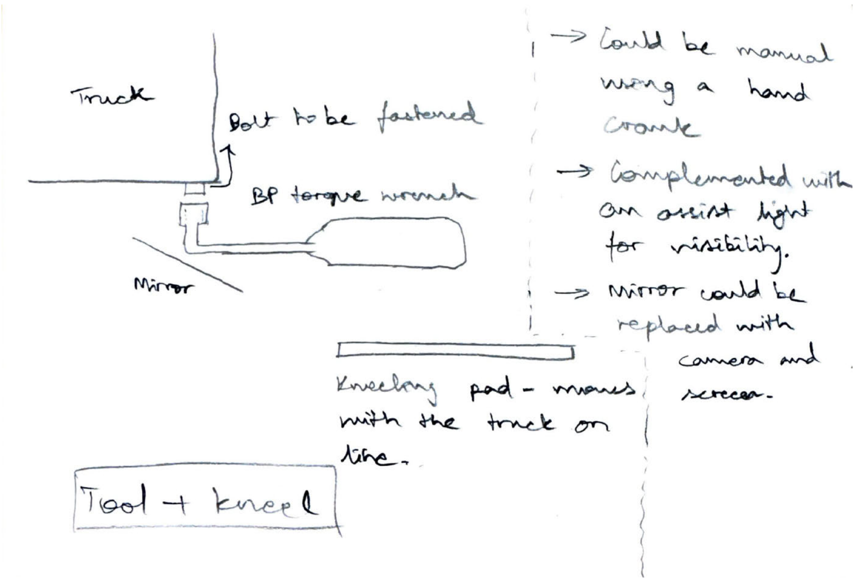


Figure 5.5: Concept 4 - Tool+kneel

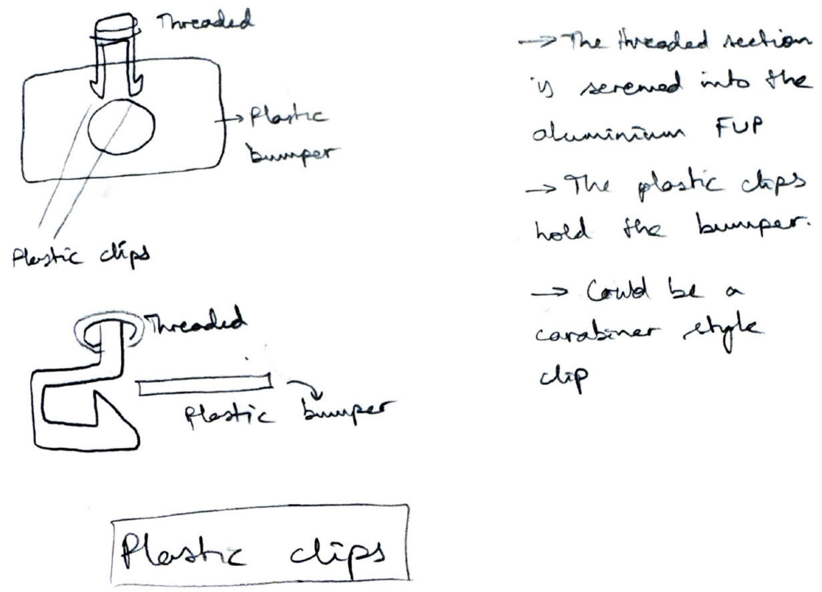
Concept 5 - Plastic clips

The M8 screws presently used to fasten the bumper could be eliminated and replaced with a snap-fit plastic clip. This would also enable a tool-less assembly process.

The clips could be circumferential or use a carabiner-style C-shape as seen in fig. 5.6.

Concept 6 - Magneto

Expanding on the tool-less assembly options, strong magnets could be used to assemble the bumper as shown in fig. 5.7. This concept was generated as a relatively low torque of 10 Nm is applied to the screws.

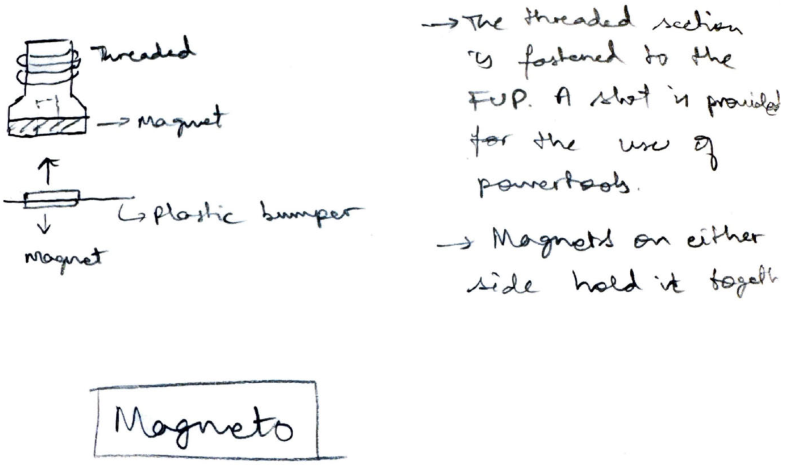


→ The threaded section is screwed into the aluminium FUP

→ The plastic clips hold the bumper.

→ Could be a carabiner style clip

Figure 5.6: Concept 5 - Plastic clips



→ The threaded section is fastened to the FUP. A slot is provided for the use of powertools.

→ Magnets on either side hold it togeth

Figure 5.7: Concept 6 - Magneto

Concept 7 - Bolt++Sticker

This solution involves replacing the standard M8 bolts with a specialised threaded rod. This rod will initially be fastened to the aluminium member using a screwdriver, after which a bolt head with internal threads will be fastened as seen in fig. 5.8. The bumper will be placed before the bolt head is assembled. As the threaded members act as dowel pins, the operator will not have to use awkward positions to locate the fasteners.

Standard stud bolts could also be used which lack a hex key slot to fasten. However, being standard fasteners, the defined fastening method could then be used.

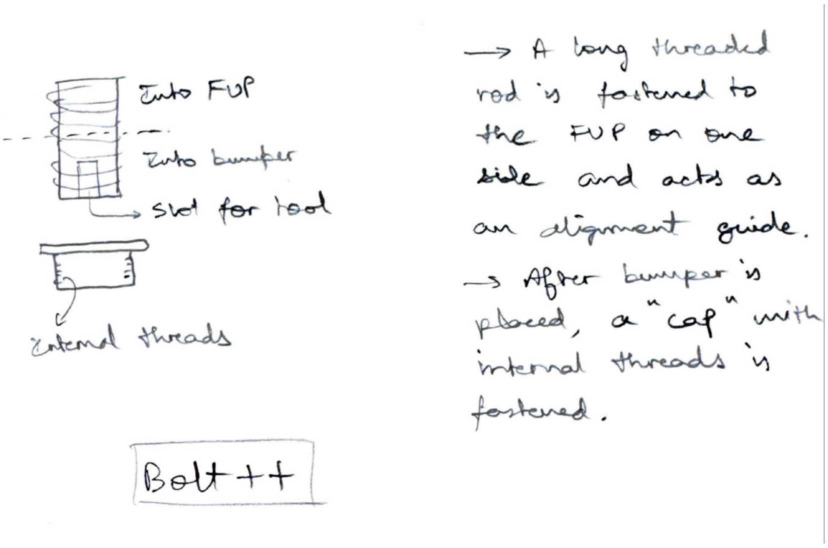


Figure 5.8: Concept 7 - Bolt++Sticker

Concept 8 - The Periscope

A periscope-like optical device could complement the standard torque wrench tool as seen in fig.5.9. The operator will use a wheeled stool to be in an ergonomically acceptable posture during assembly.

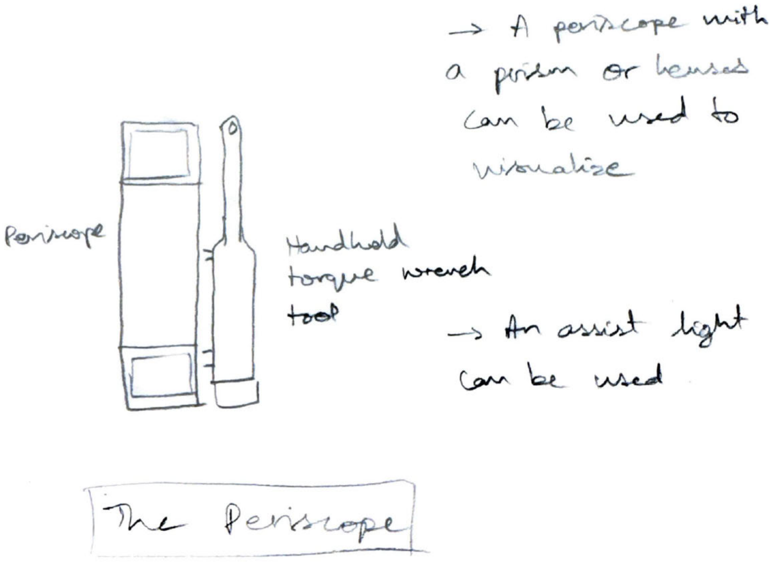


Figure 5.9: Concept 8 - The Periscope

Concept 9 - The reflecting stool

The wheeled stool being used on the main line will be fitted with a large mirror and an assist lamp to help the operator see under the truck. The assembly procedure will be carried out using the standard torque wrench. This solution has been illustrated in fig. 5.10.

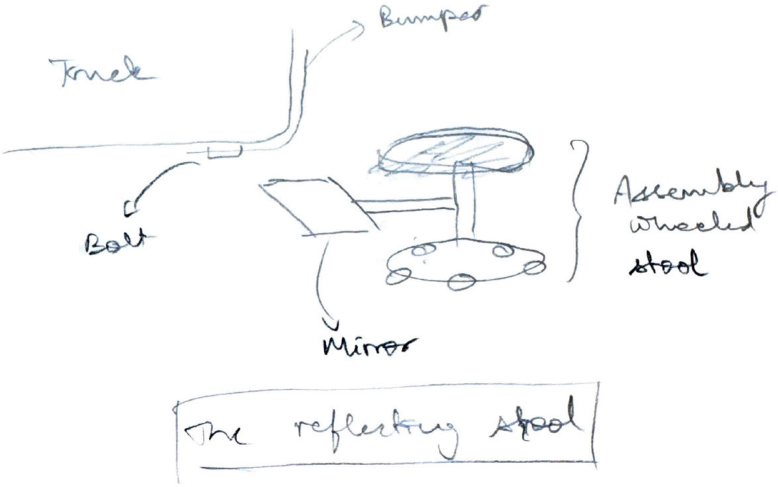


Figure 5.10: Concept 9 - The reflecting stool

5.1.4 Alignment concepts

The project team also generated 3 stand-alone alignment solution concepts for dealing with potential hole offsets between the FUP member and the bumper. Since the hole present on the bumper and the threaded hole in aluminium FUP must align for a fastener to go through, these alignment concepts were required for some but not all of the solutions presented above. A picture of this issue has been shown in fig. 5.11. This issue was identified through assembly observation.

Alignment 1 - The Handbrake

The first alignment solution is similar to a handbrake, hence the name. The solution is attached to the cab suspension cross-member with a handle at the top and a rubber boot at the bottom. The bar is spring-loaded with a ratchet mechanism to keep it in place when pulling the handle, so that the operator can let i go and it will still be able to keeps its position. An illustration of the concept can be seen in fig. 5.12

Alignment 2 - The Pendulum

The second alignment solution is also attached to the cab suspension cross-member, but this solution only relies on gravity. One of the sides is attached to the truck, see fig 5.13, while the opposite end has a weight that pulls a rubber boot against the bumper. The position of the weight can be adjusted to help distribute the alignment position.

Figure 5.11: The offset between the plastic bumper in black and the aluminium FUP in silver. Note that the threaded hole cannot be fully seen through the bumper's hole

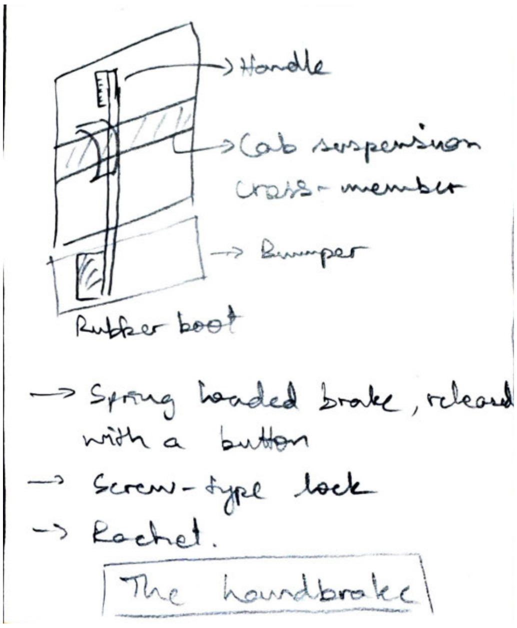


Figure 5.12: Alignment 1 - The Handbrake

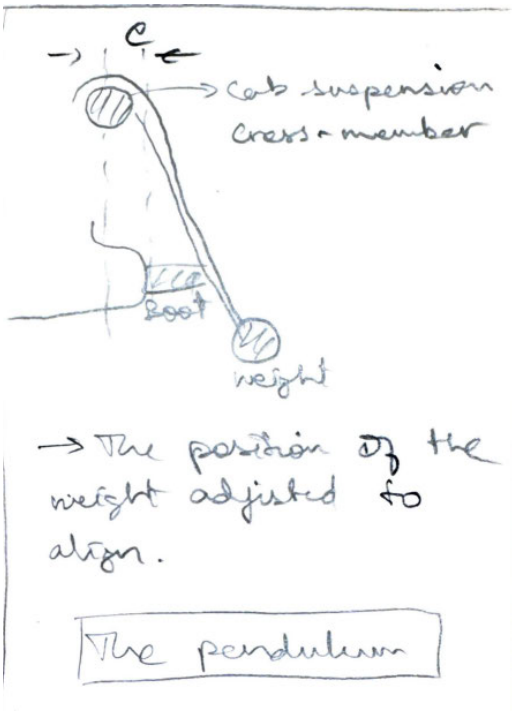


Figure 5.13: Alignment 2 - The Pendulum

Alignment 3 - The Knee/Hand

The last alignment solution is by using either the operators hand or knee to press against the bumper, while simultaneously performing the tightening operation.

5.1.5 Revised concepts

After concept screening was conducted, two new concepts were introduced while keeping the limitations of the eliminated concepts in mind.

Revised concept 1 - Camera Align

The first of the two newly generated concepts is closely related to **Hanging by truck** and as visualised in fig. 5.14 it is also attached to the cab suspension cross-member. However, this concept only acts a visual guide for the operator. The front of the hanging member will be equipped with a height adjustable screen. The screen is then connected to a camera that hangs at the bottom of member and points upwards. The solution will also have a small light equipped in close proximity to the camera, to eliminate any issues due to darkness. The assembly will be done using the standard 10 Nm tool, with the operator seated on a stool.

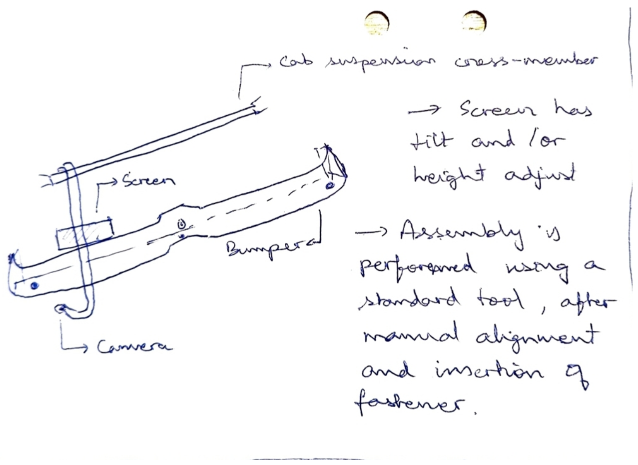


Figure 5.14: Revised concept 1 - Camera Align

Revised concept 2 - Mirror Align

The second revised concept was very similar to previous concept, with less complexity. This solution uses a tiltable mirror that goes underneath the bumper to help see the holes instead of a camera. The solution still uses the same mounting to the cab suspension cross-member as the previous concept. An illustration of the concept can be found in fig. 5.15. This concept will also use a stool for the operator to stay seated during assembly.

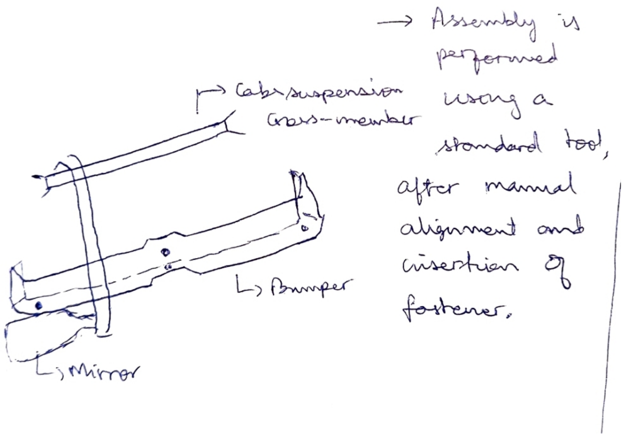


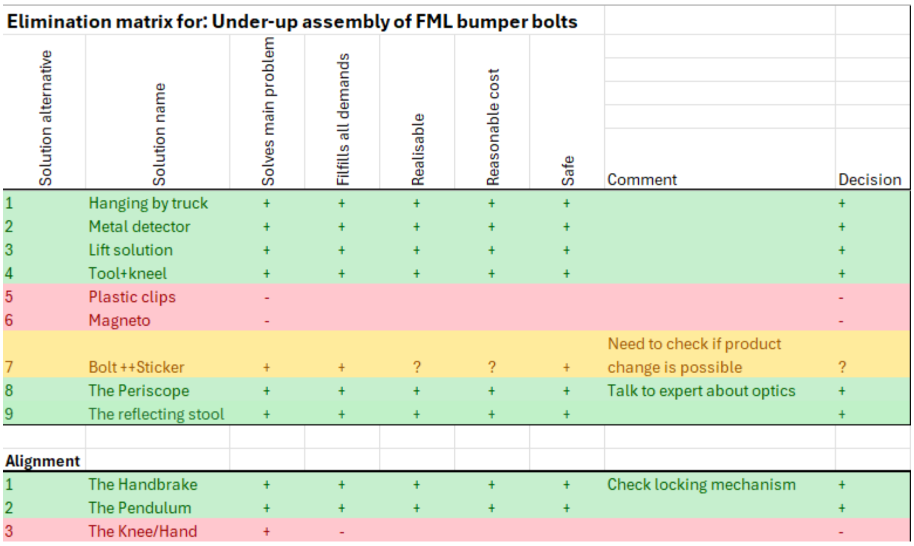
Figure 5.15: Revised concept 2 - Mirror Align

5.2 Concept elimination and screening

The screening process for this project included an elimination matrix and then two rounds of selection matrices, to eliminate concepts that did not fit with the set criteria.

5.2.1 Elimination matrix

The first matrix used for elimination only keeps the concepts that *Solves main problem*, *Fulfills all demands*, is *Realisable*, has a *Reasonable cost*, and is *Safe*. If any concept does not fulfil all of these requirements, it is immediately eliminated. From this round of elimination, the project team eliminated two concepts, *Plastic clips* and *Magneto*, since they did not fulfil the *Solve main problem* criterion. The elimination matrix is shown in fig. 5.16.



Elimination matrix for: Under-up assembly of FML bumper bolts

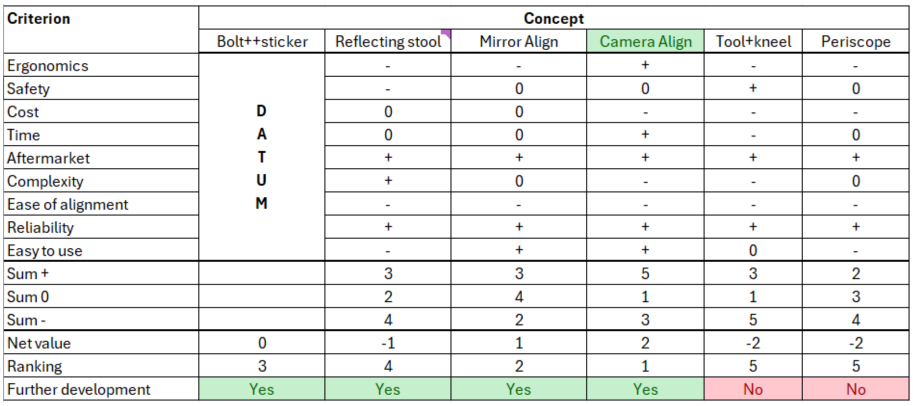
Solution alternative	Solution name	Solves main problem	Fifills all demands	Realisable	Reasonable cost	Safe	Comment	Decision
1	Hanging by truck	+	+	+	+	+		+
2	Metal detector	+	+	+	+	+		+
3	Lift solution	+	+	+	+	+		+
4	Tool+kneel	+	+	+	+	+		+
5	Plastic clips	-						-
6	Magneto	-						-
7	Bolt ++Sticker	+	+	?	?	+	Need to check if product change is possible	?
8	The Periscope	+	+	+	+	+	Talk to expert about optics	+
9	The reflecting stool	+	+	+	+	+		+
Alignment								
1	The Handbrake	+	+	+	+	+	Check locking mechanism	+
2	The Pendulum	+	+	+	+	+		+
3	The Knee/Hand	+	-					-

Figure 5.16: The elimination matrix inspired by Ulrich et al. [3]

Further, the project team generated 3 alignment solutions that also needed screening. Since there were only 3 of them, it was enough to screen them with the elimination matrix. This removed the **Knee/Hand** solution since it did not fulfil all the demands.

5.2.2 Selection matrices

The second round of elimination was done using selection matrices [3]. The project team did 3 rounds of selection and the final one is shown in fig. 5.17. The other 2 can be found in Appendix D. The first round of selection acted as a guide for round two and no decisions were taken. Each criteria in the matrix is mapped to the specifications from the target specification (table 4.4) and the connection between them can be seen in table 5.1.



Criterion	**Concept**					
	Bolt++sticker	Reflecting stool	Mirror Align	Camera Align	Tool+kneel	Periscope
Ergonomics	**D A T U M**	-	-	+	-	-
Safety		-	0	0	+	0
Cost		0	0	-	-	-
Time		0	0	+	-	0
Aftermarket		+	+	+	+	+
Complexity		+	0	-	-	0
Ease of alignment		-	-	-	-	-
Reliability		+	+	+	+	+
Easy to use		-	+	+	0	-
Sum +		3	3	5	3	2
Sum 0		2	4	1	1	3
Sum -		4	2	3	5	4
Net value	0	-1	1	2	-2	-2
Ranking	3	4	2	1	5	5
Further development	Yes	Yes	Yes	Yes	No	No

Figure 5.17: The final concept selection matrix, inspired by Ulrich et al. [3]

Criteria	Target Specifications
Ergonomics	1,3,4,11,12
Safety	2,5,6
Cost	7,10
Time	7,9,10
Aftermarket	10,14
Complexity	9,10
Ease of alignment	8,9
Reliability	13
Easy to use	8

Table 5.1: Mapping between criteria for selection matrix and the target specifications

For the second round of selection, one of the other concepts was used as datum concept. This round eliminated **Metal detector** and **Lift solution** due to them being significantly more expensive and complicated than the rest of the concepts and performing poorly in both rounds of selection. **Hanging by truck** also scored very poorly in both matrices. However, the project team decided to revise this concept and came up with two different concepts, shown in section 5.1.5.

The third and final round of selection included the 2 newly revised concepts. In this matrix the best preforming concept, **Bolt++Sticker**, from the first 2 rounds were used as datum concept. The 2 worst performing concepts were **Tool+kneel** and **Periscope**, which the project team eliminated. For the remaining concepts, prototyping was chosen as the deciding method. This was deemed easier as the prototypes were cheap and fast to develop and is a superior method compared to any analytical methods.

6

Prototyping

This chapter will cover the project team's prototyping stage. The prototypes act as a secondary evaluation method for the remaining concepts and help the project team find which concept has the most potential and could be used to solve this issue.

6.1 Test bed

A test bed was built to be able to simulate and test prototypes. The test bed was needed due to the 2 per day limit of FML's being produced on line, which limited testing. The test bed included the aluminium FUP member, plastic bumper, cab suspension cross-member, and some pulleys to help hold up the heavy structure. All of these parts were then assembled on to an aluminium-frame built in-house, to simulate the conditions of the FML on the line. A picture of the full structure can be found in fig. 6.1.

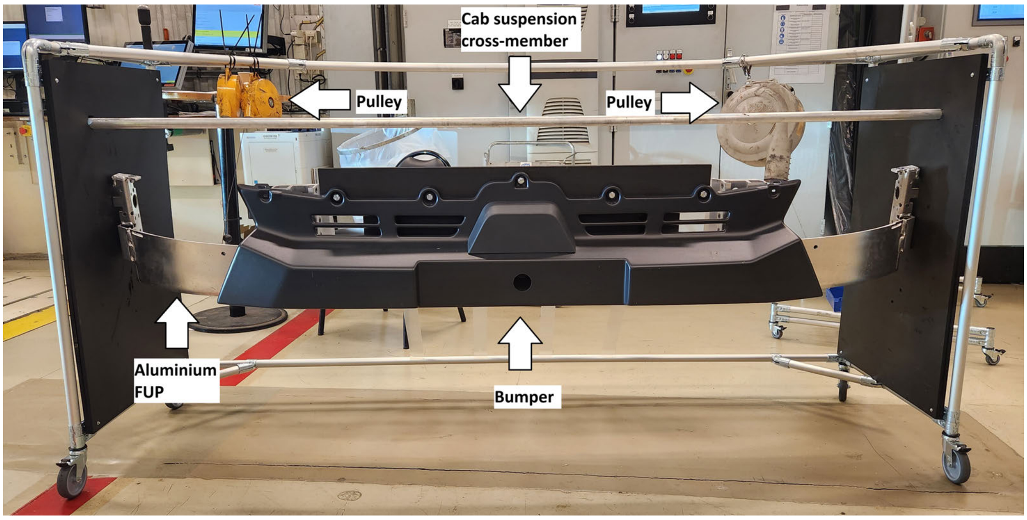


Figure 6.1: Test bed with the bumper and FUP member from the FML, with annotations for clarity

Some measurements, like the height of the bumper from the ground, were measured from the assembly line. Other measurements, like the relative position of the cab suspension cross-member, were taken from the CAD files of the truck. This was done to get an accurate representation of the real truck.

6.2 Quick and dirty

To easily visualise and understand the final concepts, making low resolution prototypes was the chosen strategy. This was done to help the project team decide on which concepts to continue to develop and to get a confirmation if a certain concept was even feasible and therefore possible to develop further.

6.2.1 Camera Align

The first concept that was prototyped was the **Camera Align**. For this prototype, most parts were designed and 3D-printed by the project team. A custom mount for the cab suspension cross-member was designed. Two phone holders with ball and socket joints were made to represent a camera and screen. The designs were taken from Thingiverse (thingiverse.com) [14] and then modified to adapt to the aluminium tubes readily available at Lean Lab Tuve. The modified part and the original are shown in fig. 6.2 and fig. 6.3. The complete prototype can be found in fig. 6.4 with one of the phones attached, and the prototype mounted on the test bed can be seen in fig. 6.5. A video call was started between the two phones to test the camera align concept.

Figure 6.2: Modified ball joint

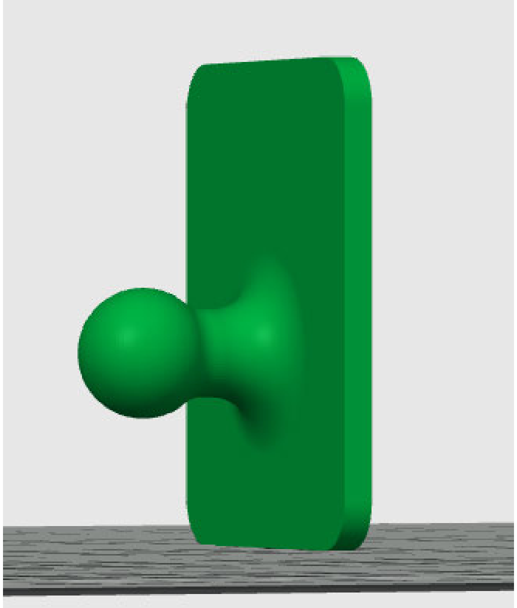


Figure 6.3: Original ball joint

Figure 6.4: Camera Align quick prototype

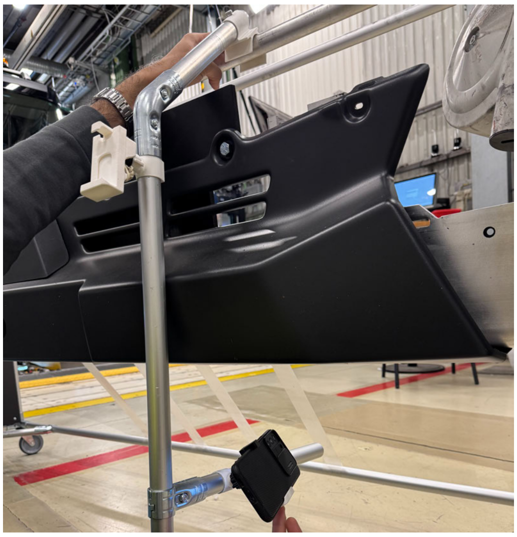


Figure 6.5: Demonstration of Camera Align on the FML

6.2.2 Bolt++Sticker

For this concept, a stud bolt and a modified flange nut was designed and 3D-printed with the M8 standard measurement. The tolerance standards were calculated using an online calculator [15]. A schematic diagram as shown in fig. 6.6 was used as a reference. The fastener, in its separated and joined states, are shown in fig. 6.7 and fig. 6.8 respectively.

The concept is printed in two parts so that the stud bolt can be assembled at the FUP sub-assembly. The stud bolts then act as dowel pins which can be used for positioning the bumper without visibility. The hex nut can then be fastened at the bumper-assembly station (station 36) to complete the assembly.
As the prototype was developed, the project team learnt that stud bolts were standard parts. However, stud bolts available within Volvo use a different type of tool for fastening and do not include a hex key as in the design, from what the project team could find. This new information was considered for further evaluation.

6.2.3 Reflective stool Mirror Align

Since the **Reflective stool** and **Mirror Align** both use the same fundamental principle of reflection, the same low-resolution prototype was deemed sufficient to evaluate feasibility. The prototype included an existing wheeled stool that is used

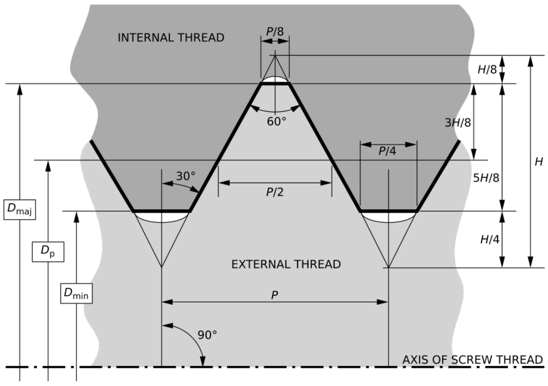


Figure 6.6: ISO and UTS Thread Dimensions diagram [16]

Figure 6.7: Bolt++Sticker parts separated

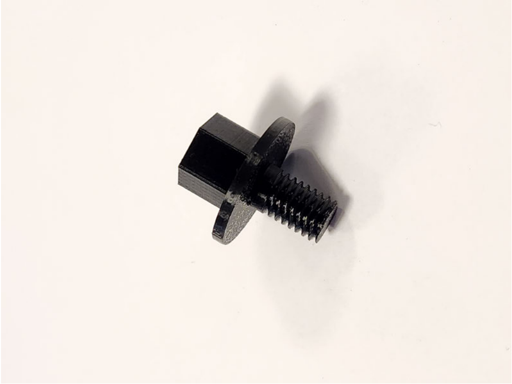


Figure 6.8: Bolt++Sticker parts joined together

on the line regularly for other assembly processes, a phone to replicate a mirror, and a book to help hold the phone in the correct position. The full prototype can be seen in fig. 6.9. It was observed that a clear view of the bolts could be achieved even with the relatively small area of 120 cm^2, which is the size of a phone screen and can be seen in fig. 6.10. However, a few key points were noted by the project team.

1. A phone screen is illuminated while a mirror is not.
2. A phone camera is wide angle. This could be emulated by a convex mirror but that could warp the image or make the movement feel unintuitive.

6.3 Review and decision for continued prototyping

After testing the quick and dirty prototypes, the project team made some decisions on which prototypes to develop further. All 4 of the final concepts worked as intended in the quick prototype stage. However, the implementation of **Bolt++Sticker** would require both product and process changes. A product change would be needed because the list of parts that goes into manufacturing a FML would change. This

Figure 6.9: Reflective stool and Mirror Align quick prototype

Figure 6.10: Reflective stool and Mirror Align visual from under the truck

is allowed by Volvo only when the truck is under development. The process change however was relatively minor and would have been possible. Due to these reasons, the **Bolt++Sticker** concept was eliminated from further development.

6.4 Higher resolution prototypes

For the next step in the prototyping stage, the project team decided to make higher resolution prototypes for user testing, solution testing, and verification.

6.4.1 Mirror Align

The first concept the project team made higher resolution prototypes for was the **Mirror Align**. For this concept, the cab suspension cross-member was used as the mounting point for the prototype. The prototype consists of a structure made up from aluminium tubes and angular metal joints. At the end of the aluminium structure, two angled mirrors were placed with the help of custom 3D-printed supports.

The mirrors needed an angle and could not be flat as the cab suspension cross-member is less wide than the bumper and FUP member. The two bolts on each side are not positioned within this width. The view from the operator's perspective to be able to see the hole and the complete assembled prototype mounted on the test bed are shown in fig. 6.11 and fig. 6.12 respectively.

Figure 6.11: The operator's view for Mirror Align, with the area of interest circled in red

Figure 6.12: Mirror Align full prototype

6.4.2 Reflective stool

For the second concept, **Reflective stool**, a custom plastic insert was designed by the project team to be able to manipulate the operator's viewing angle. The custom-designed part consists of 3 different parts, A-C, and is shown in fig. 6.13. Section A is an extension to the part to make it less likely to fall out during adjustment or if it has been poorly attached. Section B is the splined section that attaches to the aluminium pipe and each spline section allows for 22.5 degrees of rotation in either direction. Section C has the same diameter as the aluminium pipe and will be used as a support to fasten the mirror on.

The angular adjustment of 22.5 degrees was obtained by having two steps in the plastic insert (see fig. 6.13) for every step in the internal spline of the aluminium tube used. The aluminium tube was selected as this is the material readily available at Tuve Lean Lab to manufacture most of the factory's assembly trolleys. The internal structure of the pipe is shown in fig. 6.14. The pipe has 8 divisions, affording 45 degrees per rotation. To increase the resolution of rotation and provide more flexibility, two spline teeth were added for every slot in the tube, making each rotation 22.5 degrees instead.

This concept attaches to the stool via a custom C-clamp. The C-clamp has two alternative designs, which can be seen in fig. 6.15. A thorough evaluation of which one was superior could not be conducted due to time constraints. Both worked as intended and gave the operators the option to remove the tool if the stool needed

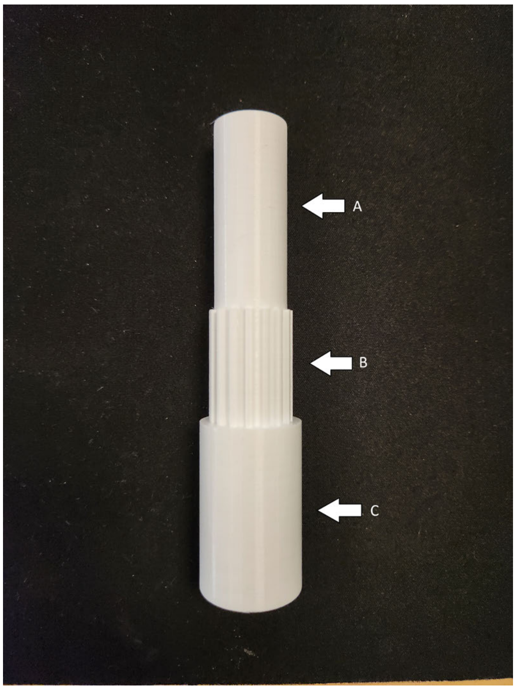


Figure 6.13: Custom plastic insert

Figure 6.14: Cross-section of the aluminium tube used

to be used for another operation or task. It achieved this using the natural compliance of plastic (PETG), which was just elastic enough to mount or unmount the equipment from the stool without using any tools.

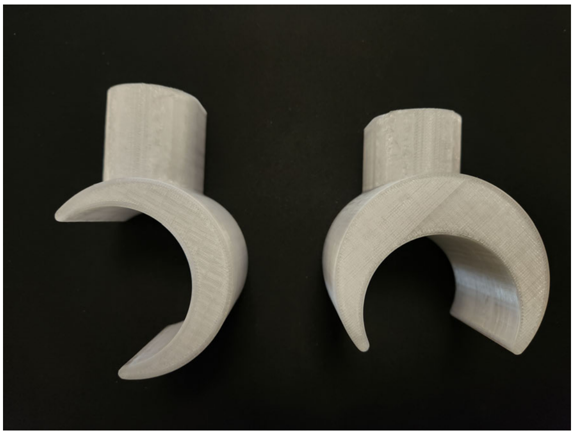


Figure 6.15: Both c-clamp iterations

From the other side of the C-clamp an aluminium pipe is attached that has the mirror and the plastic insert connected to it. The full assembly is merged together to one part and is adjustable and removable. The full prototype and the view from the operators perspective can be seen in fig. 6.16 and fig. 6.17 respectively.

Figure 6.16: Reflective stool full view prototype

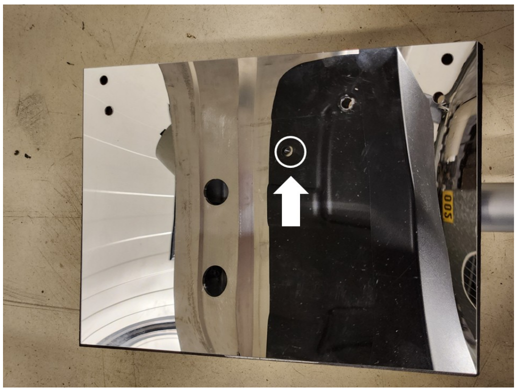


Figure 6.17: Operators view of the Reflective stool, with the region of interest highlighted

6.4.3 Camera Align

For the third and final prototype a single-board computer was used as the main component. For this project a Raspberry Pi 4 [17] was used and some additional attachments for the Raspberry Pi computer were purchased and integrated. These components are a Raspberry Pi Camera Module 3 [18], Raspberry Pi Touch Display 2 (7") [19], a 65 W Power Bank [20] and some 3D-printed parts to connect them to each other. The 3D-printed parts were mostly designed by the project team. However, some standard parts, such as a ball and socket joint [21] and a housing for the Raspberry Pi Display [22] were downloaded from Printables (www.printables.com) and redesigned to better suit the prototypes for this thesis. Fig. 6.18 shows the rear of the display-holder where the ball and socket joint is located together with a custom holder for the power bank.

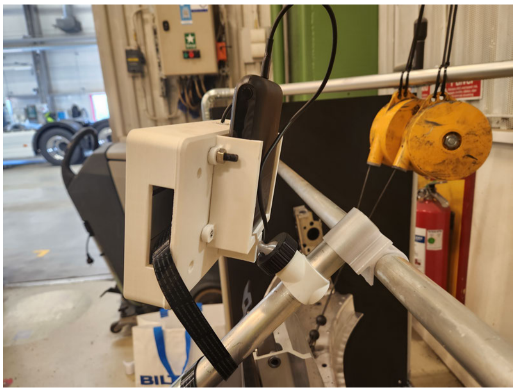


Figure 6.18: Camera Align from behind the display

Figure 6.19: Camera Align camera

The housing for the Raspberry Pi Camera was designed from the original drawings from the camera from Raspberry Pi´s website [23]. To be able to attach it to the aluminium pipe and later be able to remove it easily, a twist lock design was used. The mounted camera and housing on the prototype are shown in fig. 6.19.

Similarly to the **Mirror Align**, this prototype also makes use of the cab suspension cross-member to hang on the truck. The prototype also uses the same aluminium structure and stool set-up as **Mirror Align**. The view of the hole on the display can be seen in fig. 6.21 and the full view of the prototype in fig. 6.20.

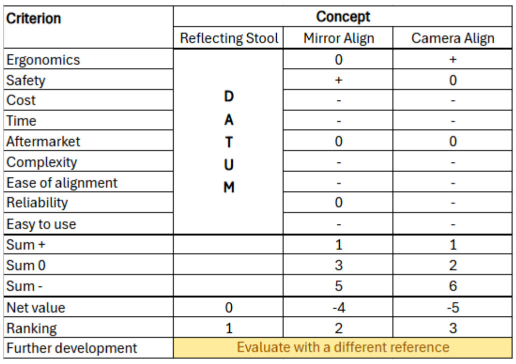
Figure 6.20: Camera Align display view

Figure 6.21: Camera Align full prototype

6.4.4 Prototype elimination by selection matrix

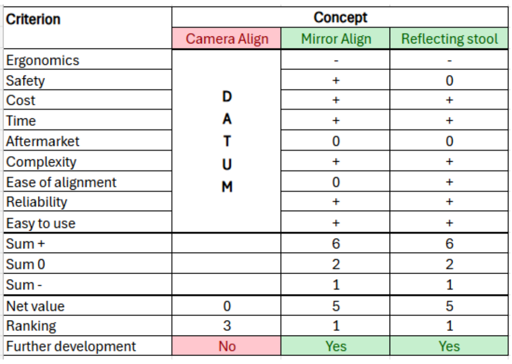
To be able to decide which concepts to further develop and test, the removal of one or more of the concepts was necessary. A selection matrix was chosen for this process. This was combined with some finding from testing, as described in Chapter 7. The criteria within the selection matrices remained the same as before from table 5.1. The first selection matrix used **Reflective stool** as a datum concept, since the other two are closer in design. From this matrix, **Reflective stool** and **Mirror Align** performed equally well, while **Camera Align** performed slightly worse. For the second selection matrix, the worst performing concept in round one, **Camera Align**, was put as the datum concept. In this matrix, both the other concepts outperformed **Camera Align**. This ultimately lead to the elimination of **Camera Align** for future testing. **Camera Align** did not pass the matrices mainly because of its complexity. The added electronics would demand more development time to "factory-proof", which would be to ensure reliable functioning despite a few drops and rough handling. It also requires a battery that must be charged and maintained, which the other two concepts do not. Both of the selection matrices can be seen in fig. 6.22 and fig. 6.23.

Two rounds of selection matrices were chosen with differing datums to ensure that the result was reliable and that differences between the concepts were clearly reflected in the results. For example, in the first matrix, **Mirror Align** and **Camera Align** are both more complex than **Reflecting Stool**, but to varying degrees.



Criterion	Concept		
	Reflecting Stool	Mirror Align	Camera Align
Ergonomics	DATUM	0	+
Safety		+	0
Cost		-	-
Time		-	-
Aftermarket		0	0
Complexity		-	-
Ease of alignment		-	-
Reliability		0	-
Easy to use		-	-
Sum +		1	1
Sum 0		3	2
Sum -		5	6
Net value	0	-4	-5
Ranking	1	2	3
Further development	Evaluate with a different reference		

Figure 6.22: Selection matrix for final prototypes



Criterion	Concept		
	Camera Align	Mirror Align	Reflecting stool
Ergonomics	DATUM	-	-
Safety		+	0
Cost		+	+
Time		+	+
Aftermarket		0	0
Complexity		+	+
Ease of alignment		0	+
Reliability		+	+
Easy to use		+	+
Sum +		6	6
Sum 0		2	2
Sum -		1	1
Net value	0	5	5
Ranking	3	1	1
Further development	No	Yes	Yes

Figure 6.23: Selection matrix for decision on prototypes

7

Testing

This chapter describes the testing of the prototypes to see if the intended purpose such as safety and ergonomics was fulfilled, first through testing by the project team and then by the intended users.

7.1 Solution testing

The fabricated prototypes were tested by the project team on the test bed and on the stopped assembly line. This was done to ensure the function of the prototype. Two main issues were uncovered during solution testing.

1. The hole for the middle bolt beneath the bumper of the FML presented a challenge, as the shape of the bumper in front of it differed from that of the other two.
2. The main assembly line in the relevant parts of the factory has a central slot through which a chain drive passes. This chain drive helps move the assembly dolly on which trucks are placed. This can be seen in figures 7.1 and 7.2. This presents a challenge as all prototypes require a wheeled stool to use effectively. The metallic lip around the slot as shown in fig. 7.1 has to be accounted for as the wheeled stool must move laterally for smooth implementation. Some parts of the line do not have the lip as shown in fig. 7.2.

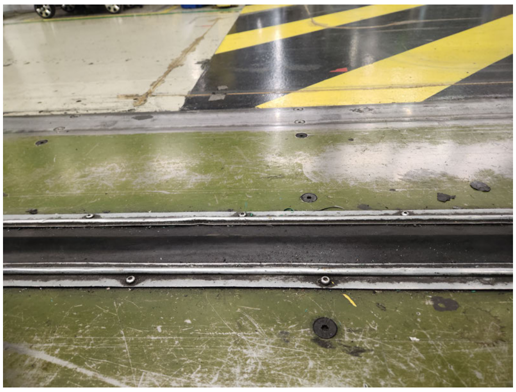


Figure 7.1: Slot through the middle of the line. Note the lip on the side

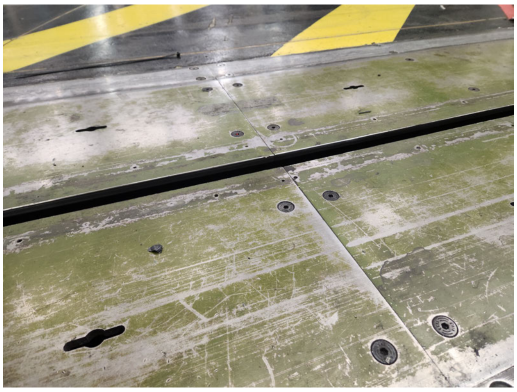


Figure 7.2: Slot through the middle of the assembly line, without a lip along its side

Most prototypes worked as intended, with minimal failures. A stool with bigger wheels, compared to the one that the project team was provided, was tested and found to be better. It traversed over the chain drive slot more smoothly. It was decided that this would be a recommendation for the final solution.

The **Camera Align** solution was also tested extensively before elimination. This evaluation helped frame a basis for the selection matrices in section 6.4.4. It required several modifications as stated below.

1. The positioning of the camera was set after testing on the test bed.
2. The camera's orientation and the code required for it to function was challenging as the solution had to feel "natural" and so the movement of objects in front of the camera had to feel intuitive. If the camera was mounted in the wrong orientation for example, the hand would move into view from the sides of the screen instead of from the bottom. Since the operator sat facing the truck, this contributed to the solution feeling unintuitive.

There were also some minor failures of glue or 3D printed components which were fixed with more thorough glue application methods or minor redesigns.

7.2 User testing

User tests were set up to evaluate the prototypes and get suggestions on how they can be improved for the final solution.

Step	Selected Method
Purpose	1. Evaluation between two prototypes. 2. Suggestions and observations that could help improve the concept. 3. User acceptance.
Survey Population	Available operators (Convenience sampling)
Survey Format	Face-to-face interaction
Concept communication means	Working prototype
Measurement of user response	Observation and semantic scales

Table 7.1: User testing methods selected as outlined by Ulrich et al. [3]

"User acceptance" has been cited as a purpose to understand if the operators will use the proposed solution in practise. This was selected as a criterion as it was brought to the project team's attention that operators often skip the recommended equipment for a task if it means saving a small amount of time. The semantic scales and the interview questions used have been enclosed in Appendix E.

The following steps were followed by the project team on the day of user testing. The same order was followed for every operator. The project team was aware that comparison would happen in this method, but it was deemed beneficial for the result of this project.

1. Demonstrate the assembly process using **Reflecting stool**.
2. Ask the user to fill the semantic scales and conduct the interview.
3. Demonstrate the assembly process using **Mirror align**.
4. Ask the user to fill the semantic scales and conduct the interview.

7.2.1 Results

6 users participated in the testing procedure- 4 men and 2 women. The experience level ranged from 2 to over 25 years with 3 users having over 25 years. Some key concerns raised by the operators have been stated below.

1. The lighting on the moving assembly line might be poorer than test conditions as the truck blocks light underneath.
2. A test must be conducted on the moving assembly line to inspire more confidence in the operation as the static test bed may be less challenging.
3. The visibility could be improved with a telescope mechanism that lets the operator move the mirror further under the truck being assembled.

The users reported that there was very little to no mental strain using these solutions. The reflecting stool however, performed better in this regard. The semantic scales helped uncover further key findings which have been stated below.

Reflecting stool

1. All operators but 2 deemed that the visibility was either "Neutral" or positive.
2. The assembly procedure scale received mixed responses. 3 operators reported positive results, 1 remained neutral, and 2 reported negative. However, the positive results were "Very easy" in two cases and the negative was never "Very difficult".
3. All operators but 1 reported that the process was "Somewhat uncomfortable". This was due to the bending that was required to clearly visualise the assembly area's reflection in the mirrors.
4. All operators but 1 reported strongly positive results for mental effort, expressing that it was not complex. 1 result was neutral.
5. Operators reported mostly neutral responses, with 1 positive and 1 negative response to the likelihood of adoption. Further probing during interviews revealed that all 6 shared the same concern about using the equipment on the moving line.

Mirror align

This concept performed worse in every measured criterion. Since the **Reflecting stool** and **Mirror align** were tested in succession, the operators stated their preference for **Reflecting stool** without prompt. The key reasons have been cited below.

1. This concept's inability to move with the operator without intervention, in contrast to **Reflecting stool** which moves with the stool.
2. The angle of the mirrors made it harder to visualise the area clearly.
3. 1 operator also expressed concern about the equipment potentially damaging the truck being assembled, as it is mounted on the truck itself.

The users also informed that they did not find the system to adjust the angle of the mirror in **Reflective Stool** very helpful.

These results helped the project team eliminate **Mirror align** from further development. Some key takeaways for the project team for the final prototype of **Reflecting stool** have been stated below.

1. Inclusion of a telescopic mechanism by modifying the now eliminated angle adjustment system for adjustable reach and visibility.
2. Protection for the mirror surface to prevent scratches and damage in the factory environment.
3. Removal of sharp edges for safe handling.
4. Suggestion to place the equipment close to the tool used for assembly to enable easier adoption of the proposed solution on the assembly line.

A request was also made to the relevant department at Volvo to investigate the usage of a shorter tool to perform the assembly. The excessive bending by the operators was due to them being unable to get closer to the assembly area. This was caused by the length of the tool as observed by the project team.

7.3 Final solution

The concerns during user tests were noted and changes were made to the design of the winning concept, the **Reflecting Stool**. This concept's adoption is also supported by the improved risk assessment as seen in Appendix B.4, MEC worksheet as seen in Appendix C.5, and REBA evaluation as seen in Appendix C.6. The results in both the REBA and Risk assessment clearly showed that the new solution was superior to the current state. The REBA reported a score of 3 for the new solution versus 4 and 11 for the current state and assembly without equipment respectively. The risk assessment reported fewer risks with lower severity. The MEC shows better results, however it could be argued that the REBA is more indicative than MEC due to the MEC being heavily influenced by frequency. A full picture of the final concept can be seen in fig. 7.3.

Figure 7.3: The final prototype used for assembly line testing

The final prototype was tested on the moving assembly line by one operator, for the production of a Volvo FML. Although further testing on the moving assembly line would be ideal, it was not possible because of the project's time constraints and the 2 per day production limit of the Volvo FML at Tuve. It fulfilled the intended purpose and worked as intended. There were however two concerns raised by the operator.

1. Although the fastener under the FML was visible, it could be greatly improved by the inclusion of a light.
2. It could be challenging for the stool to cross the central chain drive without the operator standing up to do so.

8

Discussion

This chapter aims to reflect on the obtained results and answer the set research questions.

8.1 Final prototype testing

The final prototype worked as intended. The problems encountered were expected by the project team. The lack of an assist light in the prototype was to keep the design simple and prevent additional maintenance of electronics, such as charging or occasional repairs. Larger wheels could be used on the assembly stool to solve the problem of getting over the metallic lip lining the central chain drive. Although two sizes of wheels were tested, further time and investigation is necessary to make the equipment use as smooth as possible.

Despite the trade-offs made in this prototype, the successful assembly operation on the moving line proved that the solution functioned as intended and met the targets set by the project team. The test also implied that the solution fulfilled a TRL of 7.

The ergonomics measurements of sitting eye height, sitting reach height, and elbow grip length could not be recorded by the project team as originally intended. This was due to each member having to engage 2 to 3 operators at the same time, as they were volunteering their break time for user testing. The semantic scales and interview questions were prioritised. If concerns are reported by the users, it could be beneficial to conduct a more thorough user test, record these measurements, and see if a co-relation can be drawn between the concerns reported and the user's anthropometric measurements, which was also the intent behind this user test's design.

8.2 Target specifications

To make sure that the final solution was developed with the correct specifications, a revisit of the initial specifications (Table 4.4) was conducted. The specifications were however targeted towards a new tool rather than an overall solution. This makes the target specification somewhat outdated, but still relevant to check if the final solution fulfils the criteria set by the project team.

Some notable ideal values that the final solution recorded, that were set in the initial specification were:

1. No. of new assembly steps - 1
2. No. of new tools - 0
3. Mental strain - 5, where 1 is the worst value and 5 is best value from user testing semantic scales as shown in Appendix E.1
4. Easy to use - 5 from the semantic scales
5. Perceived weight - less than 3 kg
6. Reaction force - 0 N
7. Posture- Green colour from MEC and REBA
8. Safe to use - Green colour in all assessed risks in the risk assessment, calculated using the risk matrix as shown in Appendix B.1

Both the *No. of new assembly steps* and *No. of new tools* were achieved due to the final solution being an equipment rather than a tool and the only added assembly step is to to place the mirror on the stool. The word "Tool" was perceived as a power tool used to perform fastening processes within Volvo, which is why the project team decided to term the solution and any other machine not used to directly drive a fastener as "equipment".

Mental strain and *Easy to use* was gathered from the user test. Although the sample size was fairly small due to the lack of available operators, the results were favourable. The values for these could probably be better with more users testing. However, as mentioned previously, the 2 per day limit of FML models being produced limited the testing of the solution before the end of the project.

Perceived weight and *Reaction force* display ideal values due to there not being any new tools. The equipment does add some weight, but with the main components being made from aluminium and plastic, the weight could be considered fairly negligible.

Lastly, both *Posture* and *Safe to use* were verified by doing another round of REBA which can be found in Appendix C.6, MEC found in Appendix C.5 and Risk assessment found in Appendix B.4 for the final solution. While the risk assessment does not have risks only in the green region, it does indicate significant risk reduction.

8.3 Ethics

Research ethics played a relatively small role in how the project was conducted. This was likely due to the lack of any testing closely with other people apart from the project team for large parts of the project. However, since a large number of interviews were conducted across the project, consent for data collection was always obtained at the start of the interview. Although most personnel did not mind their personal information being logged, some chose to keep it anonymous, which was respected by the project group. Names and any other identification means have been carefully omitted throughout the report and all recorded information outside of the written report will be erased upon thesis submission.

During user testing, there were ethical considerations blocking the project team from asking the participants during user testing from attempting the assembly operation without assistive equipment like in fig. 1.4. This was planned initially to understand if the users find the proposed solution useful compared to no special equipment. Although the test bed was static and free from the risks associated with a moving assembly line, the load on several joints including the neck and knee was deemed too high.

8.4 Sustainability

The solution contributes well to social and economical sustainability. Socially, it improves the assembly position and enables safe operation, offering a benefit to the operators. This can be inferred by the safety and ergonomics analyses.

An information search was conducted to understand the economic impact of the solution on Volvo. Since this information was deemed confidential by the organisation, the results cannot be published in this report. However, the study strongly supported economic sustainability. The solution itself is also fast and cheap to manufacture and repair, supporting this cause further.

Due to time constraints, environmental sustainability could not be analysed using a tool like Ansys Granta EduPack [24]. This tool could have been used to analyse recycle-ability, carbon impact, and also find more suitable materials with desired properties. Currently, the solution uses PETG, acrylic, and polycarbonate (PC) plastic parts mounted to an aluminium tube. Stainless steel fasteners are used for attachment.

8.5 Backlog

Although a functioning prototype was built and tested, there were a few tasks that were planned but could not be completed related to the chosen solution, **Reflecting stool**.

1. Detailed engineering drawings of the designed parts.
2. A full list of suppliers for the parts used, and a supplier for the mirror used which was obtained from Biltema (biltema.se).
3. Fatigue testing, especially for the compliant plastic part that clipped on and off the assembly stool.
4. Detailed research exploring the possibility of using a shorter power tool for lesser bending during assembly.

8.6 Usage of AI and LLMs

Two LLMs were used during this project- ChatGPT (chatgpt.com) and Grok (grok.com). They were used in the following ways.

1. To find interesting products during Information Search.
2. To write references in BibTex form for Overleaf.
3. To debug parts of Overleaf code, mainly with regards to formatting.

For the scope of this project, LLMs were effective to only debug overleaf code and were not very helpful for finding products or generating ideas. While some image generation was attempted to visualise schematic diagrams, they proved largely unhelpful. No information, text or image, was uploaded to either of these services and the prompts contained no confidential information.

8.7 Challenges

The biggest challenge to this project was the 2 per day production limit of the Volvo FML on the assembly line. More reliable testing could have been conducted directly on the product if it were more frequent. However, the test bed mitigated a good number of the shortcomings and proved to be a good decision, despite requiring several days of work by the project team.

The fairly traditional waterfall methodology with lean principles-inspired testing proved effective. Time did not feel like an issue for solving the main problem in most parts of the project. A better plan could have been made for prototyping material procurement by the project team. To save costs and be frugal with the materials ordered, the project team waited until the concepts were finalised to order the parts, which caused a delay in the fabrication and testing of prototypes. Since the prototyping material ordered was relatively inexpensive, a decision could have been made earlier to shorten or eliminate this delay.

The detailed research on ergonomics methods available proved to be critical towards the end of the project. The MEC worksheet encompassed all problem areas in production line ergonomics, but proved to be ineffective for the low-frequency case tackled by the project team. However, REBA analysis proved very helpful and mitigated those shortcomings. The MEC worksheet ensured no major areas were missed by the team.

Lastly, three different body measurements were deemed appropriate for user tests. However, owing to the time constraints during testing, it was not possible for the project team to measure the participants. The interview process was in-reality, multi-to-one, where the two members of the project team were engaging 2 to 3 users at the same time. This could not be avoided as the users were invited during their breaks and worked on strict shift timings. Instead, their stature height was asked and noted, which ultimately did not yield definitive co-relations.

8.8 Future work

As for future work, the project team had two concepts that had the potential to work given additional time and budget. These are listed below and were good solutions in isolation, but deemed unsuitable for this project mainly because of the 2 per day production limit of the FML.

1. **Bolt++Sticker** concept is an elegant solution that could be developed further if more time and money were available. A suggestion is that Volvo develop it after the thesis if they really like it. The solution required a product change which was not possible, as has been addressed earlier.
2. **Camera Align** as a concept could be more versatile and must be developed further for under-up assembly. Ensuring reliability and robustness of electronics in a factory environment was a challenge in this project. It was also agreed that it was too complex a solution for this particular problem.

9

Conclusion

This Master's thesis set out to help Volvo Trucks in Tuve to develop a possible solution to be able to tighten bolts with no visibility located under the truck on the main production line. This was done with a large focus on ergonomics and safety to ensure that the final product/prototype is on par with Volvo's standards regarding to safety and ergonomics. This thesis also had some research questions that will be covered below.

In total, 4 research questions were set in the beginning of this project. They have been answered below, from the obtained results.

1. **What requirements are placed on the solution for it to be useful in the assembly environment?** - This was answered by the detailed target specifications shown in table 4.4.

2. **How can good ergonomics be ensured for the intended purpose?** - Good ergonomics were ensured by avoiding extreme angles on any joints. This was verified by using the REBA method and suggesting revisions to other parts of the process that were out of scope for this project, or the project team did not have time to work on. This was mostly successful, as the ergonomics and safety were kept within acceptable margins while ensuring that the main problem was addressed. The REBA worksheets can be found in Appendix C.

3. **What changes are required to the system/process and by which stakeholders to ensure usefulness and usage of the solution?** - This question was answered in two steps.
   (a) The solution had to be accepted by the relevant production engineer, relevant safety officer, and the ergonomists. Production engineers were important as they could judge whether time was available to integrate the proposed solution to the existing assembly workflow.
   (b) The users, which in this case were the operators, had to accept the solution. Positive responses from the users during user testing indicate a likelihood that this new solution might be used in their practise.

4. **Who is affected by this project? How does it add value to said people?** - The following people were most affected by this project:
   (a) Volvo as an organisation due to the economic benefit.
   (b) The line operators due to a safer and more comfortable way of performing

the assembly.

(c) The adjustment area operators as they do not have to do an assembly their area is not designed to support. It also frees up their time.

(d) The production engineers in-charge of both the main line and the adjustment areas, as their personnel will be performing the processes they are intended to.

In conclusion, all the research questions set by the project team were answered and the final prototype seems to be a good solution for the operators to use on the production line. However, this is a solution to a current problem of having bolts underneath the truck, but the ultimate solution would be to remove any bolts under the truck and try to have a redesign to put these in more easily accessible areas to make the process faster and safer.

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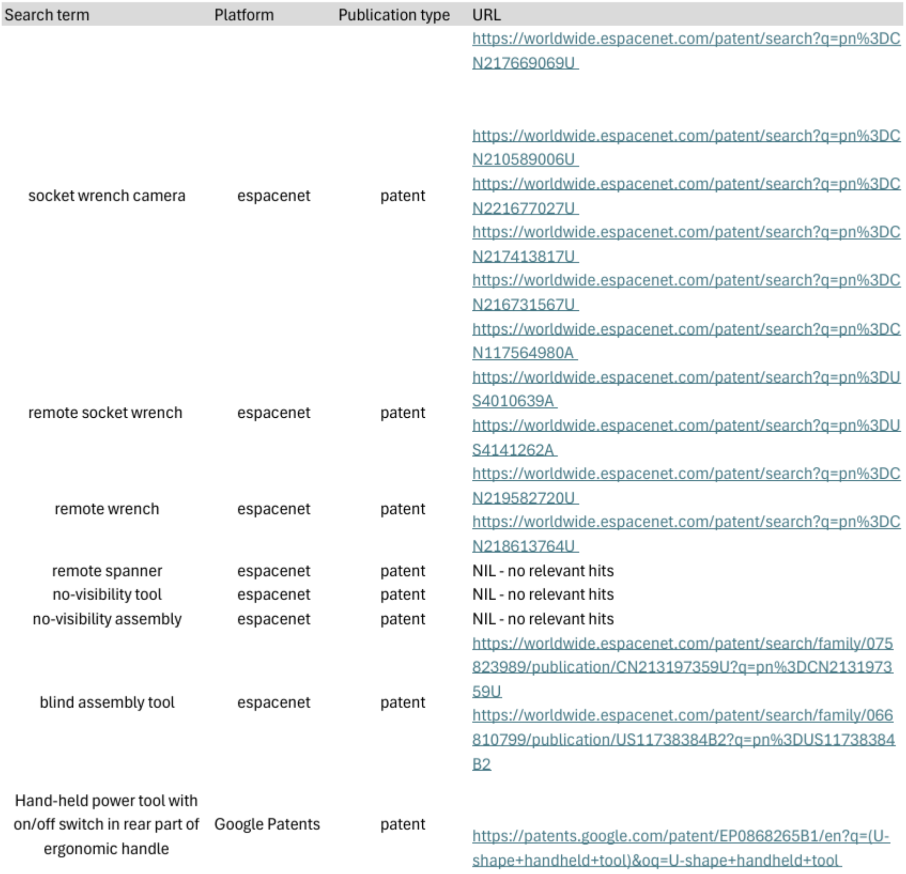
A

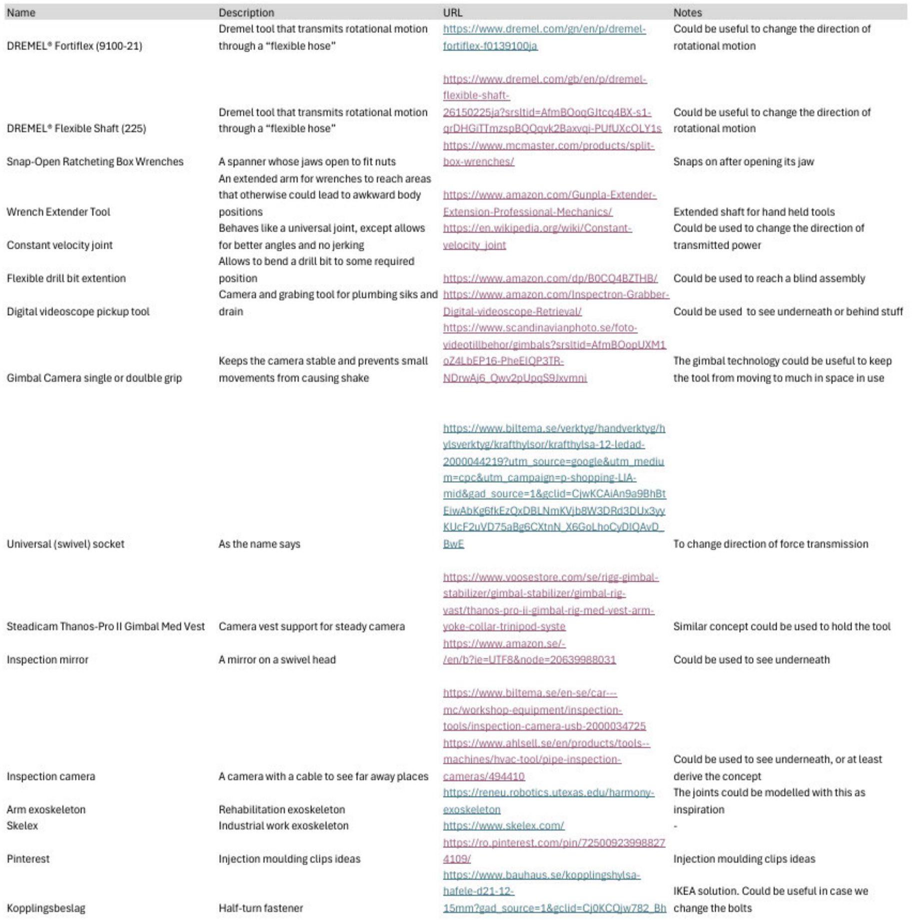
Appendix A-Information search

A.1 Patent Search



Search term	Platform	Publication type	URL
socket wrench camera	espacenet	patent	https://worldwide.espacenet.com/patent/search?q=pn%3DCN217669069U https://worldwide.espacenet.com/patent/search?q=pn%3DCN210589006U https://worldwide.espacenet.com/patent/search?q=pn%3DCN221677027U https://worldwide.espacenet.com/patent/search?q=pn%3DCN217413817U https://worldwide.espacenet.com/patent/search?q=pn%3DCN216731567U https://worldwide.espacenet.com/patent/search?q=pn%3DCN117564980A
remote socket wrench	espacenet	patent	https://worldwide.espacenet.com/patent/search?q=pn%3DUS4010639A https://worldwide.espacenet.com/patent/search?q=pn%3DUS4141262A
remote wrench	espacenet	patent	https://worldwide.espacenet.com/patent/search?q=pn%3DCN219582720U https://worldwide.espacenet.com/patent/search?q=pn%3DCN218613764U
remote spanner	espacenet	patent	NIL - no relevant hits
no-visibility tool	espacenet	patent	NIL - no relevant hits
no-visibility assembly	espacenet	patent	NIL - no relevant hits
blind assembly tool	espacenet	patent	https://worldwide.espacenet.com/patent/search/family/075823989/publication/CN213197359U?q=pn%3DCN213197359U https://worldwide.espacenet.com/patent/search/family/066810799/publication/US11738384B2?q=pn%3DUS11738384B2
Hand-held power tool with on/off switch in rear part of ergonomic handle	Google Patents	patent	https://patents.google.com/patent/EP0868265B1/en?q=(U-shape+handheld+tool)&oq=U-shape+handheld+tool

A.2 Product Search

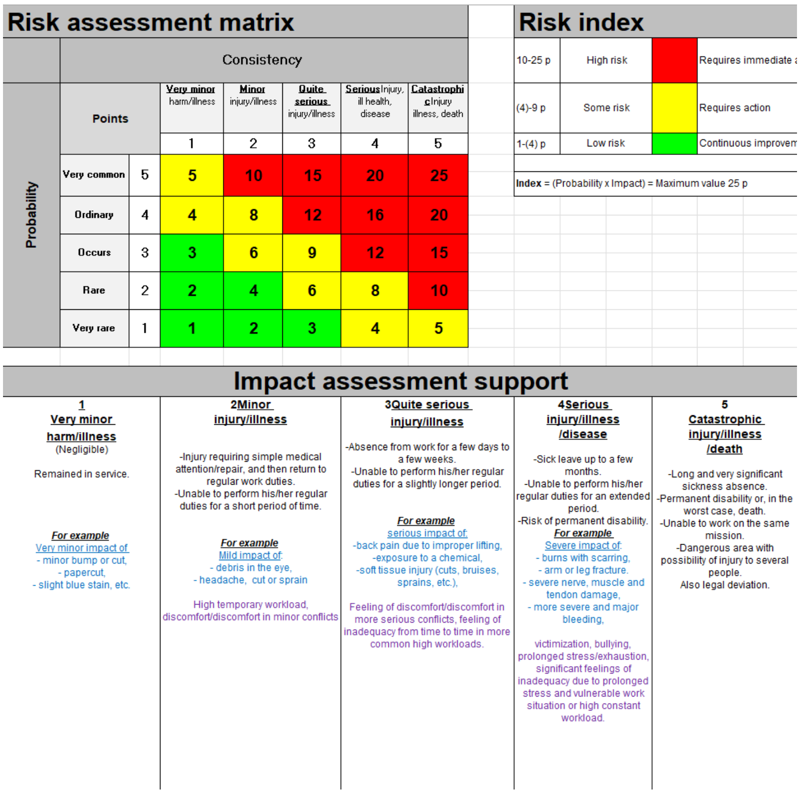


Name	Description	URL	Notes
DREMEL® Fortiflex (9100-21)	Dremel tool that transmits rotational motion through a “flexible hose”	https://www.dremel.com/gn/en/p/dremel-fortiflex-f0139100ja	Could be useful to change the direction of rotational motion
DREMEL® Flexible Shaft (225)	Dremel tool that transmits rotational motion through a “flexible hose”	https://www.dremel.com/gb/en/p/dremel-flexible-shaft-26150225ja?srsltid=AfmBOoqGJtcq4BX-s1-qrDHGiTTmzspBQQqvk2Baxvqi-PUfUXcOLY1s	Could be useful to change the direction of rotational motion
Snap-Open Ratcheting Box Wrenches	A spanner whose jaws open to fit nuts	https://www.mcmaster.com/products/split-box-wrenches/	Snaps on after opening its jaw
Wrench Extender Tool	An extended arm for wrenches to reach areas that otherwise could lead to awkward body positions	https://www.amazon.com/Gunpla-Extender-Extension-Professional-Mechanics/	Extended shaft for hand held tools
Constant velocity joint	Behaves like a universal joint, except allows for better angles and no jerking	https://en.wikipedia.org/wiki/Constant-velocity_joint	Could be used to change the direction of transmitted power
Flexible drill bit extention	Allows to bend a drill bit to some required position	https://www.amazon.com/dp/B0CQ4BZTHB/	Could be used to reach a blind assembly
Digital videoscope pickup tool	Camera and grabing tool for plumbing siks and drain	https://www.amazon.com/Inspectron-Grabber-Digital-videoscope-Retrieval/	Could be used to see underneath or behind stuff
Gimbal Camera single or doulble grip	Keeps the camera stable and prevents small movements from causing shake	https://www.scandinavianphoto.se/foto-videotillbehor/gimbals?srsltid=AfmBOopUXM1oZ4LbEP16-PheEIQP3TR-NDrwAj6_Qwv2pUpqS9Jxvmni	The gimbal technology could be useful to keep the tool from moving to much in space in use
Universal (swivel) socket	As the name says	https://www.biltema.se/verktyg/handverktyg/hylsverktyg/krafthylsor/krafthylsa-12-ledad-2000044219?utm_source=google&utm_medium=cpc&utm_campaign=p-shopping-LIA-mid&gad_source=1&gclid=CjwKCAiAn9a9BhBtEiwAbKg6fkEzQxDBLNmKVjb8W3DRd3DUx3yyKUcF2uVD75aBg6CXtnN_X6GoLhoCyDIQAvD_BwE	To change direction of force transmission
Steadicam Thanos-Pro II Gimbal Med Vest	Camera vest support for steady camera	https://www.voosestore.com/se/rigg-gimbal-stabilizer/gimbal-stabilizer/gimbal-rig-vast/thanos-pro-ii-gimbal-rig-med-vest-arm-yoke-collar-trinipod-syste	Similar concept could be used to hold the tool
Inspection mirror	A mirror on a swivel head	https://www.amazon.se/-/en/b?ie=UTF8&node=20639988031	Could be used to see underneath
Inspection camera	A camera with a cable to see far away places	https://www.biltema.se/en-se/car---mc/workshop-equipment/inspection-tools/inspection-camera-usb-2000034725 https://www.ahlsell.se/en/products/tools--machines/hvac-tool/pipe-inspection-cameras/494410	Could be used to see underneath, or at least derive the concept
Arm exoskeleton	Rehabilitation exoskeleton	https://reneu.robotics.utexas.edu/harmony-exoskeleton	The joints could be modelled with this as inspiration
Skelex	Industrial work exoskeleton	https://www.skelex.com/	-
Pinterest	Injection moulding clips ideas	https://ro.pinterest.com/pin/725009239988274109/	Injection moulding clips ideas
Kopplingsbeslag	Half-turn fastener	https://www.bauhaus.se/kopplingshylsa-hafele-d21-12-15mm?gad_source=1&gclid=Cj0KCQjw782_Bh	IKEA solution. Could be useful in case we change the bolts

B

Appendix B-Risk assessment

B.1 Risk matrix



Risk assessment matrix

			Consistency				
Probability	Points		**Very minor** harm/illness	**Minor** injury/illness	**Quite serious** injury/illness	**Serious** Injury, ill health, disease	**Catastrophic** Injury illness, death
			1	2	3	4	5
	Very common	5	🟨 5	🟥 10	🟥 15	🟥 20	🟥 25
	Ordinary	4	🟨 4	🟨 8	🟥 12	🟥 16	🟥 20
	Occurs	3	🟩 3	🟨 6	🟨 9	🟥 12	🟥 15
	Rare	2	🟩 2	🟩 4	🟨 6	🟨 8	🟥 10
	Very rare	1	🟩 1	🟩 2	🟩 3	🟨 4	🟨 5

Risk index

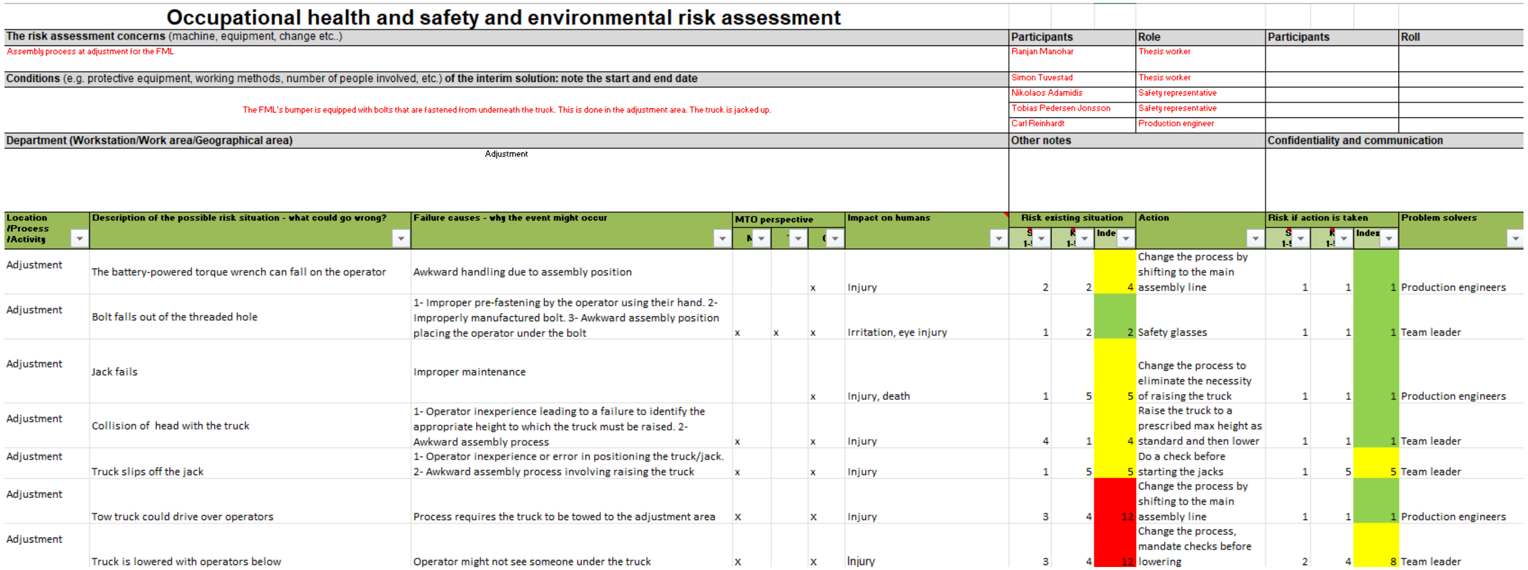
10-25 p	High risk	🟥	Requires immediate
(4)-9 p	Some risk	🟨	Requires action
1-(4) p	Low risk	🟩	Continuous improvem

Index = (Probability x Impact) = Maximum value 25 p

Impact assessment support

1 **Very minor harm/illness** (Negligible)	**2Minor injury/illness**	**3Quite serious injury/illness**	**4Serious injury/illness /disease**	**5** **Catastrophic injury/illness /death**
Remained in service.	-Injury requiring simple medical attention/repair, and then return to regular work duties. -Unable to perform his/her regular duties for a short period of time.	-Absence from work for a few days to a few weeks. -Unable to perform his/her regular duties for a slightly longer period.	-Sick leave up to a few months. -Unable to perform his/her regular duties for an extended period. -Risk of permanent disability.	-Long and very significant sickness absence. -Permanent disability or, in the worst case, death. -Unable to work on the same mission. -Dangerous area with possibility of injury to several people. Also legal deviation.
For example Very minor impact of - minor bump or cut, - papercut, - slight blue stain, etc.	***For example*** Mild impact of: - debris in the eye, - headache, cut or sprain	***For example*** serious impact of: -back pain due to improper lifting, -exposure to a chemical, -soft tissue injury (cuts, bruises, sprains, etc.),	***For example*** Severe impact of: - burns with scarring, - arm or leg fracture. - severe nerve, muscle and tendon damage, - more severe and major bleeding,	
	High temporary workload, discomfort/discomfort in minor conflicts	Feeling of discomfort/discomfort in more serious conflicts, feeling of inadequacy from time to time in more common high workloads.	victimization, bullying, prolonged stress/exhaustion, significant feelings of inadequacy due to prolonged stress and vulnerable work situation or high constant workload.	

B.2 Risk assessment-Adjustment



Occupational health and safety and environmental risk assessment

The risk assessment concerns (machine, equipment, change etc..)

Assembly process at adjustment for the FML

Conditions (e.g. protective equipment, working methods, number of people involved, etc.) **of the interim solution: note the start and end date**

The FML's bumper is equipped with bolts that are fastened from underneath the truck. This is done in the adjustment area. The truck is jacked up.

Department (Workstation/Work area/Geographical area)

Adjustment

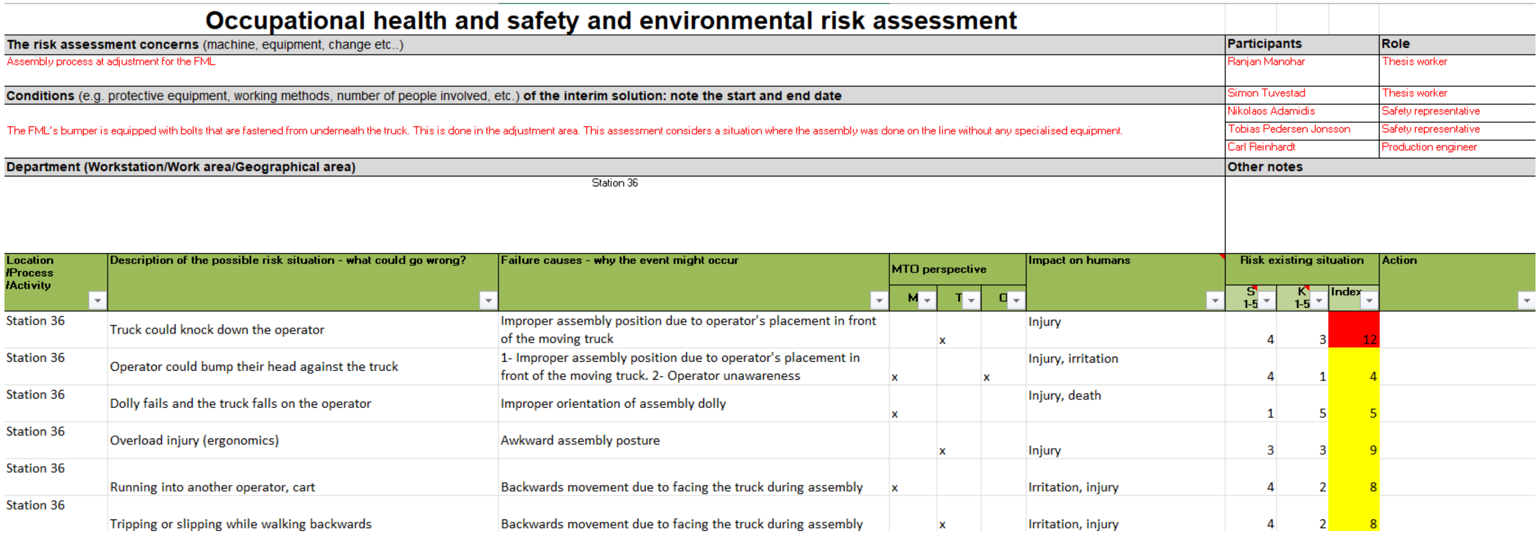
Participants	Role	Participants	Roll
Ranjan Manohar	Thesis worker		
Simon Tuvestad	Thesis worker		
Nikolaos Adamidis	Safety representative		
Tobias Pedersen Jonsson	Safety representative		
Carl Reinhardt	Production engineer		

Other notes

Confidentiality and communication

Location /Process /Activity	Description of the possible risk situation - what could go wrong?	Failure causes - why the event might occur	MTO perspective			Impact on humans	Risk existing situation			Action	Risk if action is taken			Problem solvers
							S 1-	K 1-	Inde		S 1-	K 1-	Index	
Adjustment	The battery-powered torque wrench can fall on the operator	Awkward handling due to assembly position			x	Injury	2	2	4	Change the process by shifting to the main assembly line	1	1	1	Production engineers
Adjustment	Bolt falls out of the threaded hole	1- Improper pre-fastening by the operator using their hand. 2- Improperly manufactured bolt. 3- Awkward assembly position placing the operator under the bolt	x	x	x	Irritation, eye injury	1	2	2	Safety glasses	1	1	1	Team leader
Adjustment	Jack fails	Improper maintenance			x	Injury, death	1	5	5	Change the process to eliminate the necessity of raising the truck	1	1	1	Production engineers
Adjustment	Collision of head with the truck	1- Operator inexperience leading to a failure to identify the appropriate height to which the truck must be raised. 2- Awkward assembly process	x		x	Injury	4	1	4	Raise the truck to a prescribed max height as standard and then lower	1	1	1	Team leader
Adjustment	Truck slips off the jack	1- Operator inexperience or error in positioning the truck/jack. 2- Awkward assembly process involving raising the truck	x		x	Injury	1	5	5	Do a check before starting the jacks	1	5	5	Team leader
Adjustment	Tow truck could drive over operators	Process requires the truck to be towed to the adjustment area	X		x	Injury	3	4	12	Change the process by shifting to the main assembly line	1	1	1	Production engineers
Adjustment	Truck is lowered with operators below	Operator might not see someone under the truck	X		x	Injury	3	4	12	Change the process, mandate checks before lowering	2	4	8	Team leader

B.3 Risk assessment-Line



Occupational health and safety and environmental risk assessment

The risk assessment concerns (machine, equipment, change etc..)

Assembly process at adjustment for the FML

Conditions (e.g. protective equipment, working methods, number of people involved, etc.) **of the interim solution: note the start and end date**

The FML's bumper is equipped with bolts that are fastened from underneath the truck. This is done in the adjustment area. This assessment considers a situation where the assembly was done on the line without any specialised equipment.

Department (Workstation/Work area/Geographical area)

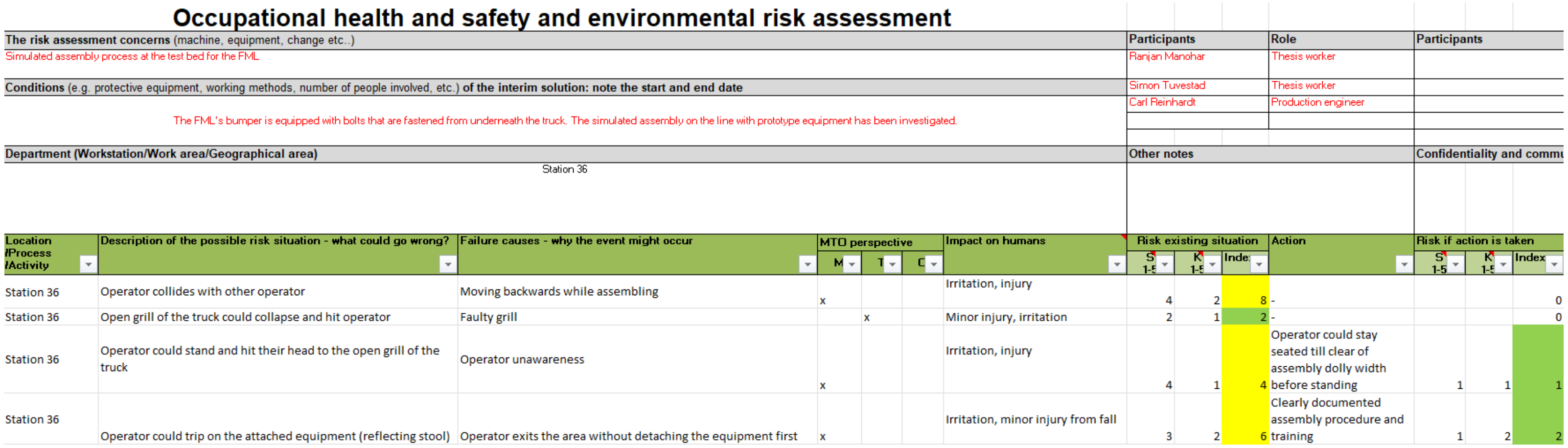
Station 36

Participants	**Role**
Ranjan Manohar	Thesis worker
Simon Tuvestad	Thesis worker
Nikolaos Adamidis	Safety representative
Tobias Pedersen Jonsson	Safety representative
Carl Reinhardt	Production engineer

Other notes

Location /Process /Activity	Description of the possible risk situation - what could go wrong?	Failure causes - why the event might occur	MTO perspective			Impact on humans	Risk existing situation			Action
			M	T	O		S 1-5	K 1-5	Index	
Station 36	Truck could knock down the operator	Improper assembly position due to operator's placement in front of the moving truck		x		Injury	4	3	🟥 12	
Station 36	Operator could bump their head against the truck	1- Improper assembly position due to operator's placement in front of the moving truck. 2- Operator unawareness	x		x	Injury, irritation	4	1	🟨 4	
Station 36	Dolly fails and the truck falls on the operator	Improper orientation of assembly dolly	x			Injury, death	1	5	🟨 5	
Station 36	Overload injury (ergonomics)	Awkward assembly posture		x		Injury	3	3	🟨 9	
Station 36	Running into another operator, cart	Backwards movement due to facing the truck during assembly	x			Irritation, injury	4	2	🟨 8	
Station 36	Tripping or slipping while walking backwards	Backwards movement due to facing the truck during assembly		x		Irritation, injury	4	2	🟨 8	

B.4 Risk assessment-Final prototype



Occupational health and safety and environmental risk assessment

The risk assessment concerns (machine, equipment, change etc..)

Simulated assembly process at the test bed for the FML

Conditions (e.g. protective equipment, working methods, number of people involved, etc.) **of the interim solution: note the start and end date**

The FML's bumper is equipped with bolts that are fastened from underneath the truck. The simulated assembly on the line with prototype equipment has been investigated.

Department (Workstation/Work area/Geographical area)

Station 36

Participants	**Role**	**Participants**
Ranjan Manohar	Thesis worker	
Simon Tuvestad	Thesis worker	
Carl Reinhardt	Production engineer	

Other notes

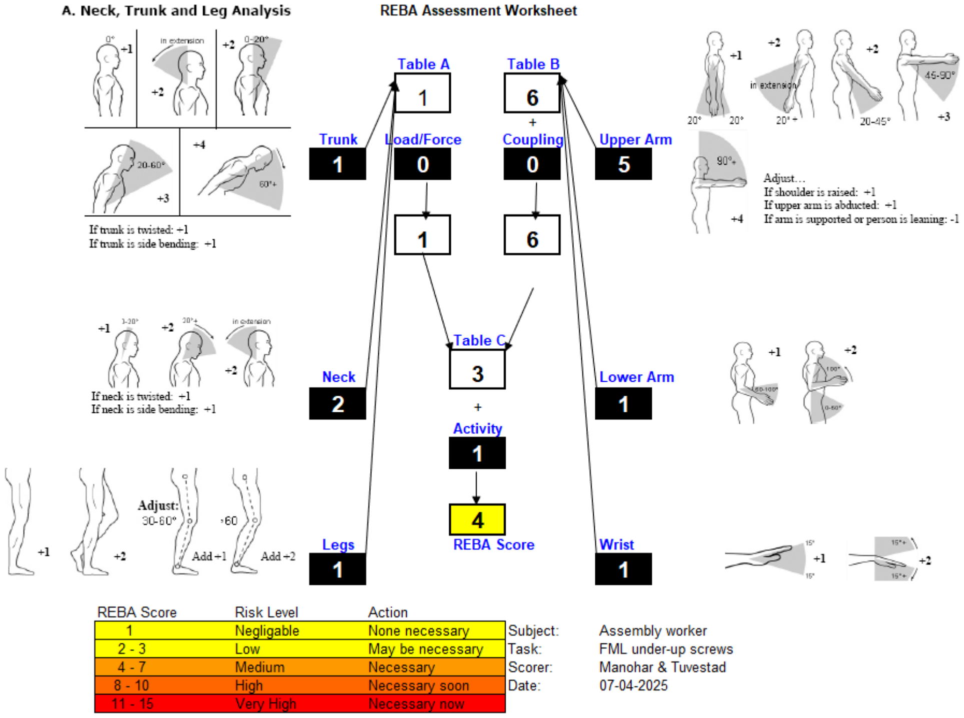
Confidentiality and commu

Location /Process /Activity	**Description of the possible risk situation - what could go wrong?**	**Failure causes - why the event might occur**	**MTO perspective**			**Impact on humans**	**Risk existing situation**			**Action**	**Risk if action is taken**		
			M	T	C		S 1-5	K 1-5	Inde		S 1-5	K 1-5	Index
Station 36	Operator collides with other operator	Moving backwards while assembling	x			Irritation, injury	4	2	8	-			0
Station 36	Open grill of the truck could collapse and hit operator	Faulty grill		x		Minor injury, irritation	2	1	2	-			0
Station 36	Operator could stand and hit their head to the open grill of the truck	Operator unawareness	x			Irritation, injury	4	1	4	Operator could stay seated till clear of assembly dolly width before standing	1	1	1
Station 36	Operator could trip on the attached equipment (reflecting stool)	Operator exits the area without detaching the equipment first	x			Irritation, minor injury from fall	3	2	6	Clearly documented assembly procedure and training	1	2	2

C

Appendix C-Current ergonomics assessment

C.1 REBA-Adjustment



A. Neck, Trunk and Leg Analysis

REBA Assessment Worksheet

If trunk is twisted: +1
If trunk is side bending: +1

If neck is twisted: +1
If neck is side bending: +1

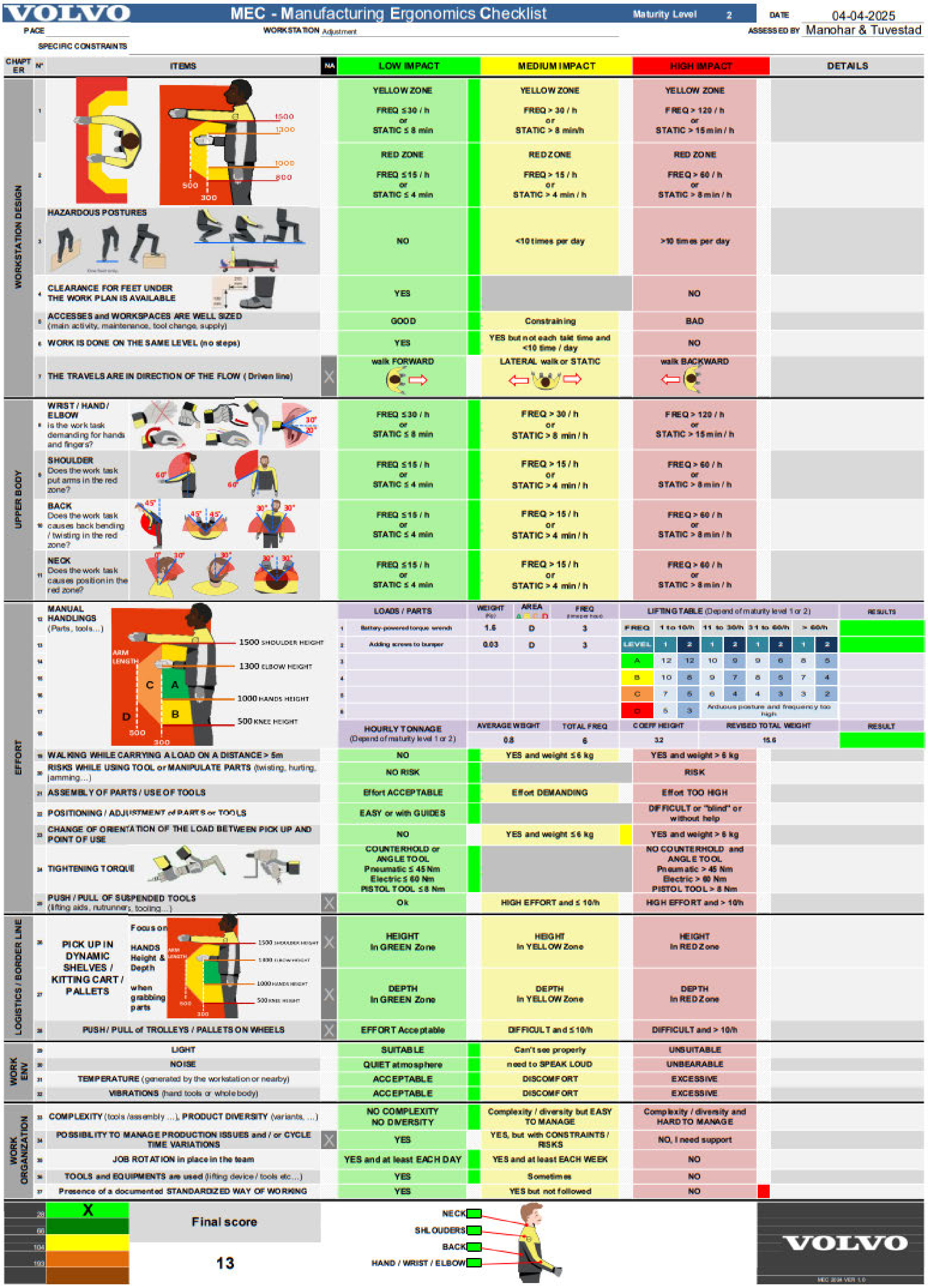
Adjust…
If shoulder is raised: +1
If upper arm is abducted: +1
If arm is supported or person is leaning: -1

Table A: 1
Table B: 6
Trunk: 1
Load/Force: 0
Coupling: 0
Upper Arm: 5
Neck: 2
Lower Arm: 1
Legs: 1
Wrist: 1
Table A + Load/Force: 1
Table B + Coupling: 6
Table C: 3
Activity: 1
REBA Score: 4

REBA Score	Risk Level	Action
1	Negligable	None necessary
2 - 3	Low	May be necessary
4 - 7	Medium	Necessary
8 - 10	High	Necessary soon
11 - 15	Very High	Necessary now

Subject: Assembly worker
Task: FML under-up screws
Scorer: Manohar & Tuvestad
Date: 07-04-2025

C.2 MEC-Adjustment



VOLVO **MEC - Manufacturing Ergonomics Checklist** Maturity Level 2

DATE 04-04-2025

PACE

WORKSTATION Adjustment

ASSESSED BY Manohar & Tuvestad

SPECIFIC CONSTRAINTS

CHAPTER	N°	ITEMS	NA	LOW IMPACT	MEDIUM IMPACT	HIGH IMPACT	DETAILS
WORKSTATION DESIGN	1			YELLOW ZONE FREQ ≤30 / h or STATIC ≤ 8 min	YELLOW ZONE FREQ > 30 / h or STATIC > 8 min/h	YELLOW ZONE FREQ > 120 / h or STATIC > 15 min / h	
	2			RED ZONE FREQ ≤15 / h or STATIC ≤ 4 min	RED ZONE FREQ > 15 / h or STATIC > 4 min / h	RED ZONE FREQ > 60 / h or STATIC > 8 min / h	
	3	HAZARDOUS POSTURES		NO	<10 times per day	>10 times per day	
	4	CLEARANCE FOR FEET UNDER THE WORK PLAN IS AVAILABLE		YES		NO	
	5	ACCESSES and WORKSPACES ARE WELL SIZED (main activity, maintenance, tool change, supply)		GOOD	Constraining	BAD	
	6	WORK IS DONE ON THE SAME LEVEL (no steps)		YES	YES but not each takt time and <10 time / day	NO	
	7	THE TRAVELS ARE IN DIRECTION OF THE FLOW (Driven line)	X	walk FORWARD	LATERAL walk or STATIC	walk BACKWARD	
UPPER BODY	8	WRIST / HAND / ELBOW Is the work task demanding for hands and fingers?		FREQ ≤30 / h or STATIC ≤ 8 min	FREQ > 30 / h or STATIC > 8 min / h	FREQ > 120 / h or STATIC > 15 min / h	
	9	SHOULDER Does the work task put arms in the red zone?		FREQ ≤15 / h or STATIC ≤ 4 min	FREQ > 15 / h or STATIC > 4 min / h	FREQ > 60 / h or STATIC > 8 min / h	
	10	BACK Does the work task causes back bending / twisting in the red zone?		FREQ ≤15 / h or STATIC ≤ 4 min	FREQ > 15 / h or STATIC > 4 min / h	FREQ > 60 / h or STATIC > 8 min / h	
	11	NECK Does the work task causes position in the red zone?		FREQ ≤15 / h or STATIC ≤ 4 min	FREQ > 15 / h or STATIC > 4 min / h	FREQ > 60 / h or STATIC > 8 min / h	

EFFORT

12–18 MANUAL HANDLINGS (Parts, tools…)

N°	LOADS / PARTS	WEIGHT (Kg)	AREA A B C D	FREQ (times per hour)
1	Battery-powered torque wrench	1.6	D	3
2	Adding screws to bumper	0.03	D	3
3				
4				
5				
6				

LIFTING TABLE (Depend of maturity level 1 or 2)

FREQ	1 to 10/h		11 to 30/h		31 to 60/h		> 60/h	
LEVEL	1	2	1	2	1	2	1	2
A	12	12	10	9	9	6	8	5
B	10	8	9	7	8	5	7	4
C	7	5	6	4	4	3	3	2
D	5	3	Arduous posture and frequency too high					

RESULTS: 🟩 🟩

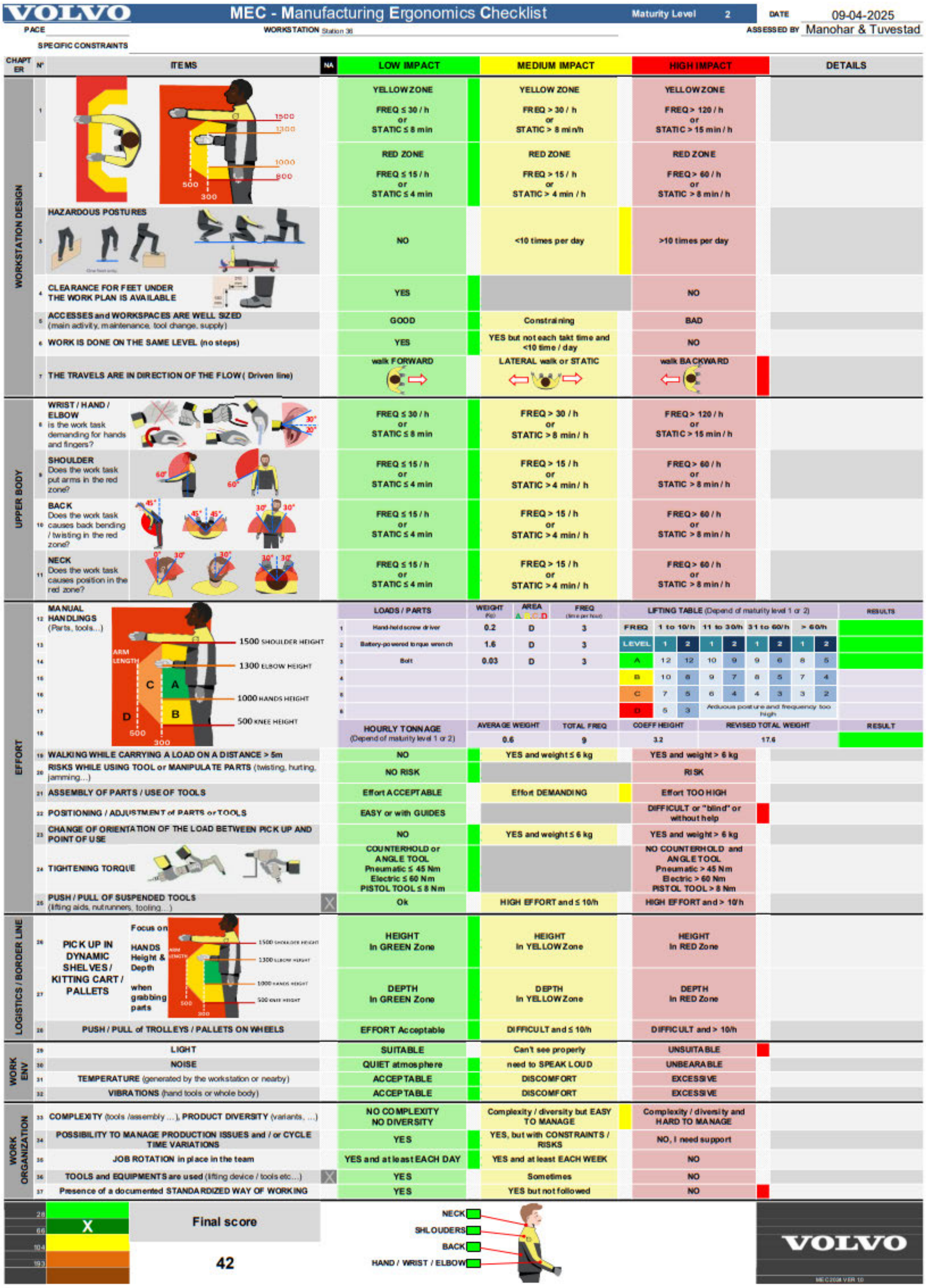
HOURLY TONNAGE (Depend of maturity level 1 or 2)	AVERAGE WEIGHT	TOTAL FREQ	COEFF HEIGHT	REVISED TOTAL WEIGHT	RESULT
	0.8	6	3.2	15.6	🟩

CHAPTER	N°	ITEMS	NA	LOW IMPACT	MEDIUM IMPACT	HIGH IMPACT	DETAILS
EFFORT	19	WALKING WHILE CARRYING A LOAD ON A DISTANCE > 5m		NO	YES and weight ≤6 kg	YES and weight > 6 kg	
	20	RISKS WHILE USING TOOL or MANIPULATE PARTS (twisting, hurting, jamming…)		NO RISK		RISK	
	21	ASSEMBLY OF PARTS / USE OF TOOLS		Effort ACCEPTABLE	Effort DEMANDING	Effort TOO HIGH	
	22	POSITIONING / ADJUSTMENT of PARTS or TOOLS		EASY or with GUIDES		DIFFICULT or "blind" or without help	
	23	CHANGE OF ORIENTATION OF THE LOAD BETWEEN PICK UP AND POINT OF USE		NO	YES and weight ≤6 kg	YES and weight > 6 kg	
	24	TIGHTENING TORQUE		COUNTERHOLD or ANGLE TOOL Pneumatic ≤ 45 Nm Electric ≤ 60 Nm PISTOL TOOL ≤8 Nm		NO COUNTERHOLD and ANGLE TOOL Pneumatic > 45 Nm Electric > 60 Nm PISTOL TOOL > 8 Nm	
	25	PUSH / PULL OF SUSPENDED TOOLS (lifting aids, nutrunners, tooling…)	X	Ok	HIGH EFFORT and ≤ 10/h	HIGH EFFORT and > 10/h	
LOGISTICS / BORDER LINE	26	PICK UP IN DYNAMIC SHELVES / KITTING CART / PALLETS Focus on HANDS Height & Depth when grabbing parts	X	HEIGHT In GREEN Zone	HEIGHT In YELLOW Zone	HEIGHT In RED Zone	
	27		X	DEPTH In GREEN Zone	DEPTH In YELLOW Zone	DEPTH In RED Zone	
	28	PUSH / PULL of TROLLEYS / PALLETS ON WHEELS	X	EFFORT Acceptable	DIFFICULT and ≤ 10/h	DIFFICULT and > 10/h	
WORK ENV	29	LIGHT		SUITABLE	Can't see properly	UNSUITABLE	
	30	NOISE		QUIET atmosphere	need to SPEAK LOUD	UNBEARABLE	
	31	TEMPERATURE (generated by the workstation or nearby)		ACCEPTABLE	DISCOMFORT	EXCESSIVE	
	32	VIBRATIONS (hand tools or whole body)		ACCEPTABLE	DISCOMFORT	EXCESSIVE	
WORK ORGANIZATION	33	COMPLEXITY (tools /assembly …), PRODUCT DIVERSITY (variants, …)		NO COMPLEXITY NO DIVERSITY	Complexity / diversity but EASY TO MANAGE	Complexity / diversity and HARD TO MANAGE	
	34	POSSIBILITY TO MANAGE PRODUCTION ISSUES and / or CYCLE TIME VARIATIONS	X	YES	YES, but with CONSTRAINTS / RISKS	NO, I need support	
	35	JOB ROTATION in place in the team		YES and at least EACH DAY	YES and at least EACH WEEK	NO	
	36	TOOLS and EQUIPMENTS are used (lifting device / tools etc…)		YES	Sometimes	NO	
	37	Presence of a documented STANDARDIZED WAY OF WORKING		YES	YES but not followed	NO	

28	X	Final score
66		
104		13
193		

NECK 🟩
SHLOUDERS 🟩
BACK 🟩
HAND / WRIST / ELBOW 🟩

C.3 MEC-Line



VOLVO **MEC - Manufacturing Ergonomics Checklist** Maturity Level 2

DATE 09-04-2025

PACE

WORKSTATION Station 36

ASSESSED BY Manohar & Tuvestad

SPECIFIC CONSTRAINTS

CHAPTER	N°	ITEMS	NA	LOW IMPACT	MEDIUM IMPACT	HIGH IMPACT	DETAILS
WORKSTATION DESIGN	1			YELLOW ZONE FREQ ≤ 30 / h or STATIC ≤ 8 min 🟩	YELLOW ZONE FREQ > 30 / h or STATIC > 8 min/h	YELLOW ZONE FREQ > 120 / h or STATIC > 15 min / h	
	2			RED ZONE FREQ ≤ 15 / h or STATIC ≤ 4 min 🟩	RED ZONE FREQ > 15 / h or STATIC > 4 min / h	RED ZONE FREQ > 60 / h or STATIC > 8 min / h	
	3	HAZARDOUS POSTURES		NO	<10 times per day 🟨	>10 times per day	
	4	CLEARANCE FOR FEET UNDER THE WORK PLAN IS AVAILABLE		YES 🟩		NO	
	5	ACCESSES and WORKSPACES ARE WELL SIZED (main activity, maintenance, tool change, supply)		GOOD 🟩	Constraining	BAD	
	6	WORK IS DONE ON THE SAME LEVEL (no steps)		YES 🟩	YES but not each takt time and <10 time / day	NO	
	7	THE TRAVELS ARE IN DIRECTION OF THE FLOW (Driven line)		walk FORWARD	LATERAL walk or STATIC	walk BACKWARD 🟥	
UPPER BODY	8	WRIST / HAND / ELBOW is the work task demanding for hands and fingers?		FREQ ≤ 30 / h or STATIC ≤ 8 min 🟩	FREQ > 30 / h or STATIC > 8 min / h	FREQ > 120 / h or STATIC > 15 min / h	
	9	SHOULDER Does the work task put arms in the red zone?		FREQ ≤ 15 / h or STATIC ≤ 4 min 🟩	FREQ > 15 / h or STATIC > 4 min / h	FREQ > 60 / h or STATIC > 8 min / h	
	10	BACK Does the work task causes back bending / twisting in the red zone?		FREQ ≤ 15 / h or STATIC ≤ 4 min 🟩	FREQ > 15 / h or STATIC > 4 min / h	FREQ > 60 / h or STATIC > 8 min / h	
	11	NECK Does the work task causes position in the red zone?		FREQ ≤ 15 / h or STATIC ≤ 4 min 🟩	FREQ > 15 / h or STATIC > 4 min / h	FREQ > 60 / h or STATIC > 8 min / h	

EFFORT — 12–18 MANUAL HANDLINGS (Parts, tools...)

	LOADS / PARTS	WEIGHT (Kg)	AREA A B C D	FREQ (time per hour)
1	Hand-held screw driver	0.2	D	3
2	Battery-powered torque wrench	1.6	D	3
3	Bolt	0.03	D	3
4				
5				
6				

LIFTING TABLE (Depend of maturity level 1 or 2)

FREQ	1 to 10/h		11 to 30/h		31 to 60/h		> 60/h		RESULTS
LEVEL	1	2	1	2	1	2	1	2	🟩
A	12	12	10	9	9	6	8	5	🟩
B	10	8	9	7	8	5	7	4	
C	7	5	6	4	4	3	3	2	
D	5	3	Arduous posture and frequency too high						

HOURLY TONNAGE (Depend of maturity level 1 or 2)	AVERAGE WEIGHT	TOTAL FREQ	COEFF HEIGHT	REVISED TOTAL WEIGHT	RESULT
	0.6	9	3.2	17.6	🟩

CHAPTER	N°	ITEMS	NA	LOW IMPACT	MEDIUM IMPACT	HIGH IMPACT	DETAILS
EFFORT	19	WALKING WHILE CARRYING A LOAD ON A DISTANCE > 5m		NO 🟩	YES and weight ≤ 6 kg	YES and weight > 6 kg	
	20	RISKS WHILE USING TOOL or MANIPULATE PARTS (twisting, hurting, jamming...)		NO RISK 🟩		RISK	
	21	ASSEMBLY OF PARTS / USE OF TOOLS		Effort ACCEPTABLE	Effort DEMANDING 🟨	Effort TOO HIGH	
	22	POSITIONING / ADJUSTMENT of PARTS or TOOLS		EASY or with GUIDES		DIFFICULT or "blind" or without help 🟥	
	23	CHANGE OF ORIENTATION OF THE LOAD BETWEEN PICK UP AND POINT OF USE		NO 🟩	YES and weight ≤ 6 kg	YES and weight > 6 kg	
	24	TIGHTENING TORQUE		COUNTERHOLD or ANGLE TOOL Pneumatic ≤ 45 Nm Electric ≤ 60 Nm PISTOL TOOL ≤ 8 Nm 🟩		NO COUNTERHOLD and ANGLE TOOL Pneumatic > 45 Nm Electric > 60 Nm PISTOL TOOL > 8 Nm	
	25	PUSH / PULL OF SUSPENDED TOOLS (lifting aids, nutrunners, tooling...)	☒	Ok	HIGH EFFORT and ≤ 10/h	HIGH EFFORT and > 10/h	
LOGISTICS / BORDER LINE	26	PICK UP IN DYNAMIC SHELVES / KITTING CART / PALLETS Focus on HANDS Height & Depth when grabbing parts		HEIGHT In GREEN Zone 🟩	HEIGHT In YELLOW Zone	HEIGHT In RED Zone	
	27			DEPTH In GREEN Zone 🟩	DEPTH In YELLOW Zone	DEPTH In RED Zone	
	28	PUSH / PULL of TROLLEYS / PALLETS ON WHEELS		EFFORT Acceptable 🟩	DIFFICULT and ≤ 10/h	DIFFICULT and > 10/h	
WORK ENV	29	LIGHT		SUITABLE	Can't see properly	UNSUITABLE 🟥	
	30	NOISE		QUIET atmosphere 🟩	need to SPEAK LOUD	UNBEARABLE	
	31	TEMPERATURE (generated by the workstation or nearby)		ACCEPTABLE 🟩	DISCOMFORT	EXCESSIVE	
	32	VIBRATIONS (hand tools or whole body)		ACCEPTABLE 🟩	DISCOMFORT	EXCESSIVE	
WORK ORGANIZATION	33	COMPLEXITY (tools /assembly ...), PRODUCT DIVERSITY (variants, ...)		NO COMPLEXITY NO DIVERSITY	Complexity / diversity but EASY TO MANAGE 🟨	Complexity / diversity and HARD TO MANAGE	
	34	POSSIBILITY TO MANAGE PRODUCTION ISSUES and / or CYCLE TIME VARIATIONS		YES 🟩	YES, but with CONSTRAINTS / RISKS	NO, I need support	
	35	JOB ROTATION in place in the team		YES and at least EACH DAY 🟩	YES and at least EACH WEEK	NO	
	36	TOOLS and EQUIPMENTS are used (lifting device / tools etc...)	☒	YES	Sometimes	NO	
	37	Presence of a documented STANDARDIZED WAY OF WORKING		YES	YES but not followed	NO 🟥	

28	🟩
66	X
104	🟨
193	🟧
	🟫

Final score

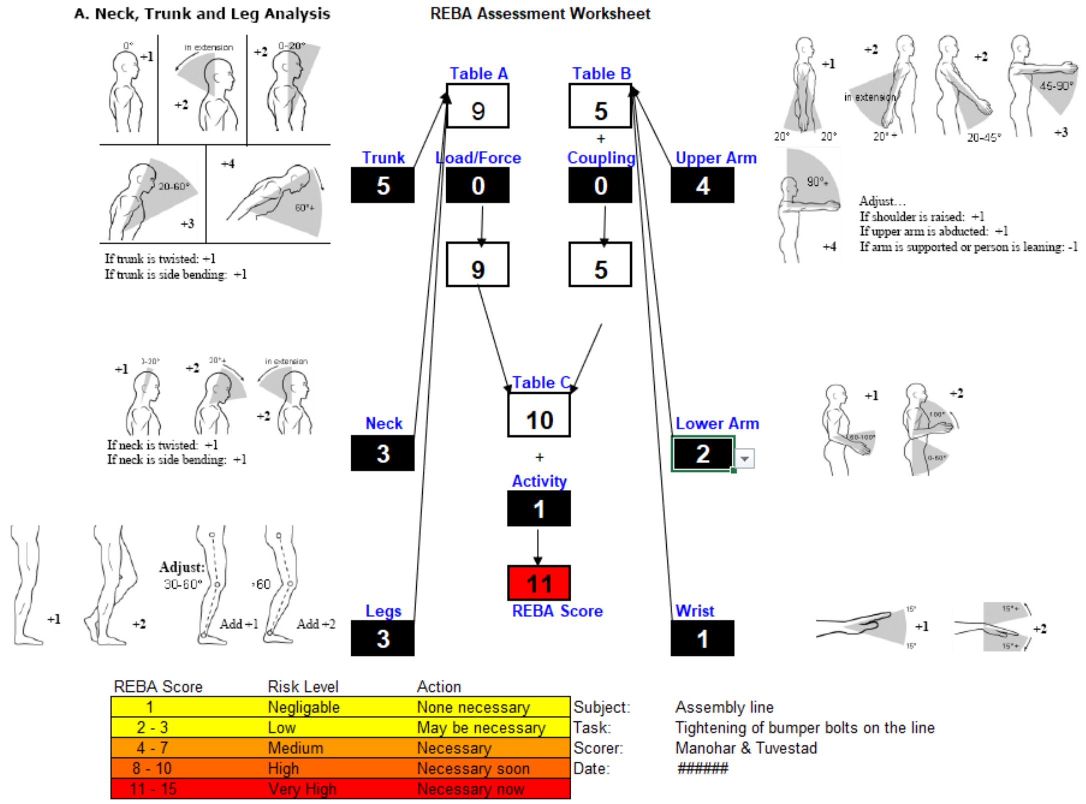
42

NECK 🟩
SHLOUDERS 🟩
BACK 🟩
HAND / WRIST / ELBOW 🟩

VOLVO

MEC2024 VER 1.0

C.4 REBA-Line



If trunk is twisted: +1
If trunk is side bending: +1

If neck is twisted: +1
If neck is side bending: +1

Adjust…
If shoulder is raised: +1
If upper arm is abducted: +1
If arm is supported or person is leaning: -1

REBA Assessment Worksheet

Table A: 9
Trunk: 5
Neck: 3
Legs: 3
Load/Force: 0
9

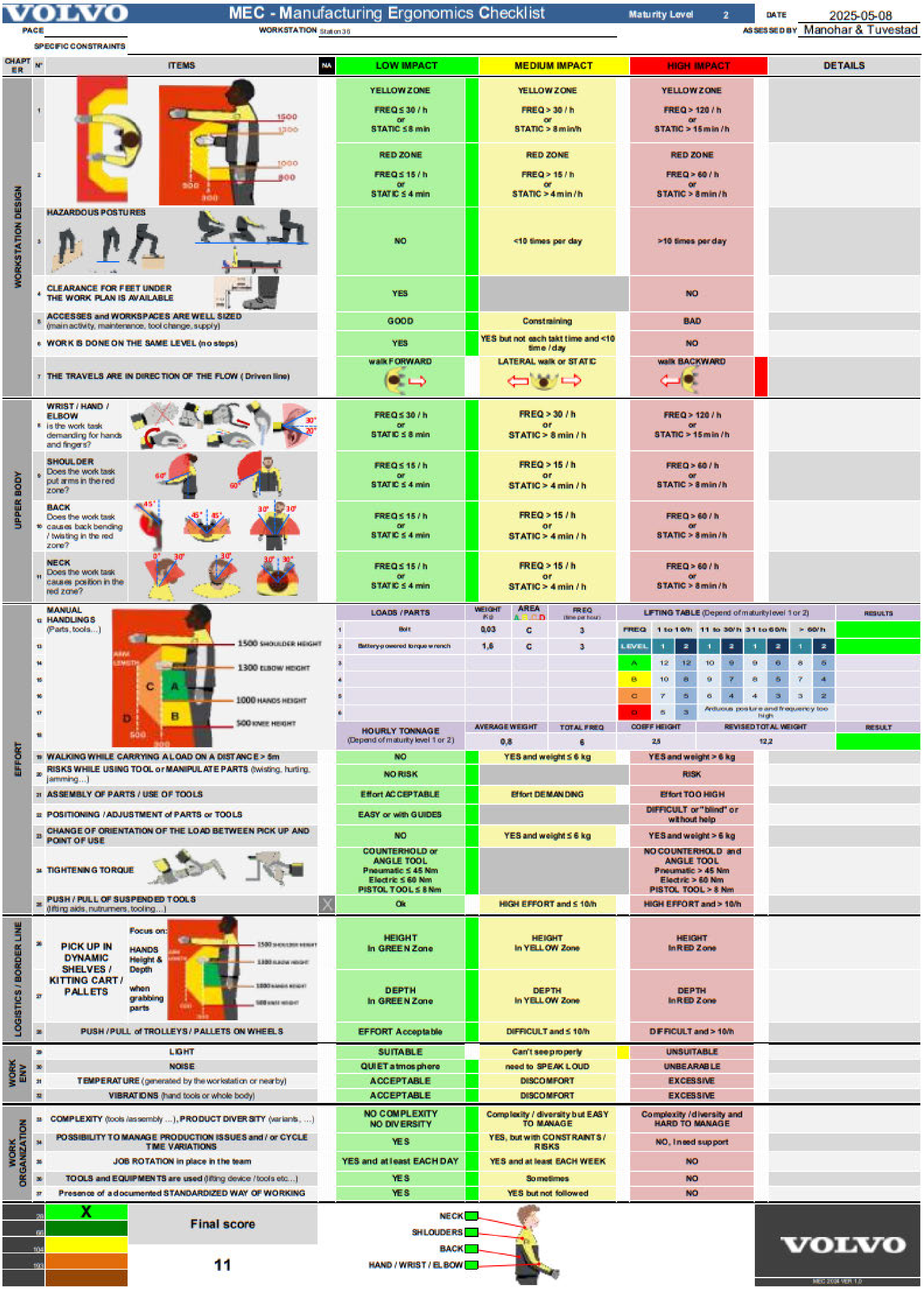
Table B: 5
+
Coupling: 0
5
Upper Arm: 4
Lower Arm: 2
Wrist: 1

Table C: 10
+
Activity: 1
11
REBA Score

REBA Score	Risk Level	Action
1	Negligable	None necessary
2 - 3	Low	May be necessary
4 - 7	Medium	Necessary
8 - 10	High	Necessary soon
11 - 15	Very High	Necessary now

Subject: Assembly line
Task: Tightening of bumper bolts on the line
Scorer: Manohar & Tuvestad
Date: ######

C.5 MEC-Final prototype



VOLVO **MEC - Manufacturing Ergonomics Checklist** Maturity Level 2

DATE 2025-05-08

PACE

WORKSTATION Station 30

ASSESSED BY Manohar & Tuvestad

SPECIFIC CONSTRAINTS

CHAPTER	N°	ITEMS	NA	LOW IMPACT		MEDIUM IMPACT		HIGH IMPACT		DETAILS
WORKSTATION DESIGN	1			YELLOW ZONE FREQ ≤ 30 / h or STATIC ≤ 8 min	🟩	YELLOW ZONE FREQ > 30 / h or STATIC > 8 min/h		YELLOW ZONE FREQ > 120 / h or STATIC > 15 min / h		
	2			RED ZONE FREQ ≤ 15 / h or STATIC ≤ 4 min	🟩	RED ZONE FREQ > 15 / h or STATIC > 4 min / h		RED ZONE FREQ > 60 / h or STATIC > 8 min / h		
	3	HAZARDOUS POSTURES		NO	🟩	<10 times per day		>10 times per day		
	4	CLEARANCE FOR FEET UNDER THE WORK PLAN IS AVAILABLE		YES	🟩			NO		
	5	ACCESSES and WORKSPACES ARE WELL SIZED (main activity, maintenance, tool change, supply)		GOOD	🟩	Constraining		BAD		
	6	WORK IS DONE ON THE SAME LEVEL (no steps)		YES	🟩	YES but not each takt time and <10 time / day		NO		
	7	THE TRAVELS ARE IN DIRECTION OF THE FLOW (Driven line)		walk FORWARD		LATERAL walk or STATIC		walk BACKWARD	🟥	
UPPER BODY	8	WRIST / HAND / ELBOW Is the work task demanding for hands and fingers?		FREQ ≤ 30 / h or STATIC ≤ 8 min	🟩	FREQ > 30 / h or STATIC > 8 min / h		FREQ > 120 / h or STATIC > 15 min / h		
	9	SHOULDER Does the work task put arms in the red zone?		FREQ ≤ 15 / h or STATIC ≤ 4 min	🟩	FREQ > 15 / h or STATIC > 4 min / h		FREQ > 60 / h or STATIC > 8 min / h		
	10	BACK Does the work task causes back bending / twisting in the red zone?		FREQ ≤ 15 / h or STATIC ≤ 4 min	🟩	FREQ > 15 / h or STATIC > 4 min / h		FREQ > 60 / h or STATIC > 8 min / h		
	11	NECK Does the work task causes position in the red zone?		FREQ ≤ 15 / h or STATIC ≤ 4 min	🟩	FREQ > 15 / h or STATIC > 4 min / h		FREQ > 60 / h or STATIC > 8 min / h		
EFFORT	12–18	MANUAL HANDLINGS (Parts, tools...)								
	19	WALKING WHILE CARRYING A LOAD ON A DISTANCE > 5m		NO	🟩	YES and weight ≤ 6 kg		YES and weight > 6 kg		
	20	RISKS WHILE USING TOOL or MANIPULATE PARTS (twisting, hurting, jamming...)		NO RISK	🟩			RISK		
	21	ASSEMBLY OF PARTS / USE OF TOOLS		Effort ACCEPTABLE	🟩	Effort DEMANDING		Effort TOO HIGH		
	22	POSITIONING / ADJUSTMENT of PARTS or TOOLS		EASY or with GUIDES	🟩			DIFFICULT or "blind" or without help		
	23	CHANGE OF ORIENTATION OF THE LOAD BETWEEN PICK UP AND POINT OF USE		NO	🟩	YES and weight ≤ 6 kg		YES and weight > 6 kg		
	24	TIGHTENING TORQUE		COUNTERHOLD or ANGLE TOOL Pneumatic ≤ 45 Nm Electric ≤ 60 Nm PISTOL TOOL ≤ 8 Nm	🟩			NO COUNTERHOLD and ANGLE TOOL Pneumatic > 45 Nm Electric > 60 Nm PISTOL TOOL > 8 Nm		
	25	PUSH / PULL OF SUSPENDED TOOLS (lifting aids, nutrunners, tooling...)	X	Ok		HIGH EFFORT and ≤ 10/h		HIGH EFFORT and > 10/h		
LOGISTICS / BORDER LINE	26	PICK UP IN DYNAMIC SHELVES / KITTING CART / PALLETS Focus on: HANDS Height & Depth when grabbing parts		HEIGHT In GREEN Zone	🟩	HEIGHT In YELLOW Zone		HEIGHT In RED Zone		
	27			DEPTH In GREEN Zone	🟩	DEPTH In YELLOW Zone		DEPTH In RED Zone		
	28	PUSH / PULL of TROLLEYS / PALLETS ON WHEELS		EFFORT Acceptable	🟩	DIFFICULT and ≤ 10/h		DIFFICULT and > 10/h		
WORK ENV	29	LIGHT		SUITABLE		Can't see properly	🟨	UNSUITABLE		
	30	NOISE		QUIET atmosphere	🟩	need to SPEAK LOUD		UNBEARABLE		
	31	TEMPERATURE (generated by the workstation or nearby)		ACCEPTABLE	🟩	DISCOMFORT		EXCESSIVE		
	32	VIBRATIONS (hand tools or whole body)		ACCEPTABLE	🟩	DISCOMFORT		EXCESSIVE		
WORK ORGANIZATION	33	COMPLEXITY (tools /assembly ...), PRODUCT DIVERSITY (variants, ...)		NO COMPLEXITY NO DIVERSITY	🟩	Complexity / diversity but EASY TO MANAGE		Complexity / diversity and HARD TO MANAGE		
	34	POSSIBILITY TO MANAGE PRODUCTION ISSUES and / or CYCLE TIME VARIATIONS		YES	🟩	YES, but with CONSTRAINTS / RISKS		NO, I need support		
	35	JOB ROTATION in place in the team		YES and at least EACH DAY	🟩	YES and at least EACH WEEK		NO		
	36	TOOLS and EQUIPMENTS are used (lifting device / tools etc...)		YES	🟩	Sometimes		NO		
	37	Presence of a documented STANDARDIZED WAY OF WORKING		YES	🟩	YES but not followed		NO		

N°	LOADS / PARTS	WEIGHT Kg	AREA A B C D	FREQ (time per hour)
1	Bolt	0,03	C	3
2	Battery-powered torque wrench	1,6	C	3
3				
4				
5				
6				

LIFTING TABLE (Depend of maturity level 1 or 2)

FREQ	1 to 10/h		11 to 30/h		31 to 60/h		> 60/h	
LEVEL	1	2	1	2	1	2	1	2
A	12	12	10	9	9	6	8	5
B	10	8	9	7	8	5	7	4
C	7	5	6	4	4	3	3	2
D	5	3	Arduous posture and frequency too high					

RESULTS: 🟩 🟩

HOURLY TONNAGE (Depend of maturity level 1 or 2)	AVERAGE WEIGHT	TOTAL FREQ	COEFF HEIGHT	REVISED TOTAL WEIGHT	RESULT
	0,8	6	2,5	12,2	🟩

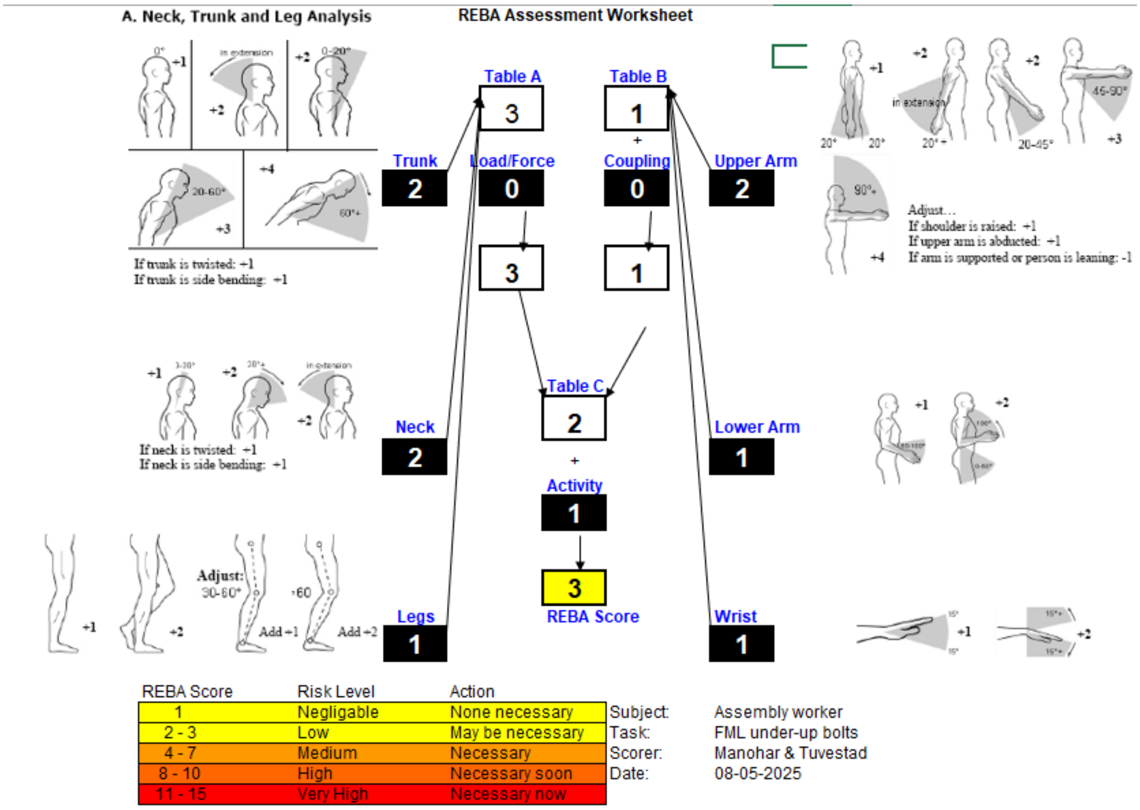
28	X	Final score
66		
104		11
193		

NECK 🟩
SHLOUDERS 🟩
BACK 🟩
HAND / WRIST / ELBOW 🟩

VOLVO

MEC 2024 VER 1.0

C.6 REBA-Final prototype



A. Neck, Trunk and Leg Analysis

REBA Assessment Worksheet

If trunk is twisted: +1
If trunk is side bending: +1

If neck is twisted: +1
If neck is side bending: +1

Adjust...
If shoulder is raised: +1
If upper arm is abducted: +1
If arm is supported or person is leaning: -1

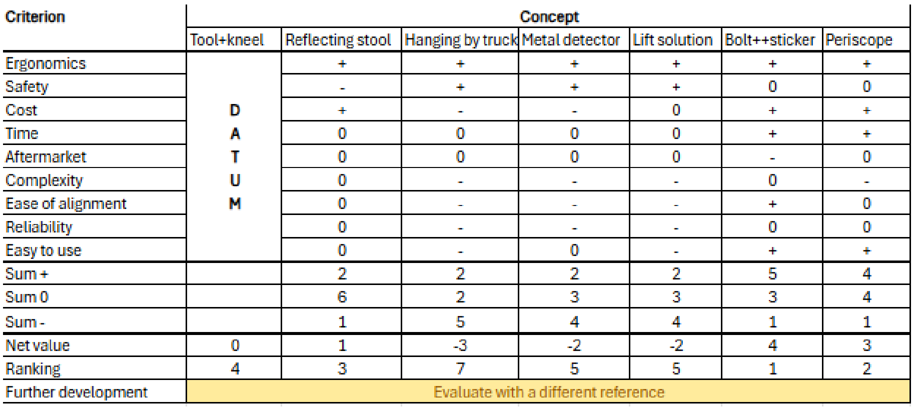
Table A: 3
Table B: 1
Trunk: 2
Load/Force: 0
Coupling: 0
Upper Arm: 2
3
1
Table C: 2
Activity: 1
REBA Score: 3
Neck: 2
Lower Arm: 1
Legs: 1
Wrist: 1

REBA Score	Risk Level	Action
1	Negligable	None necessary
2 - 3	Low	May be necessary
4 - 7	Medium	Necessary
8 - 10	High	Necessary soon
11 - 15	Very High	Necessary now

Subject: Assembly worker
Task: FML under-up bolts
Scorer: Manohar & Tuvestad
Date: 08-05-2025

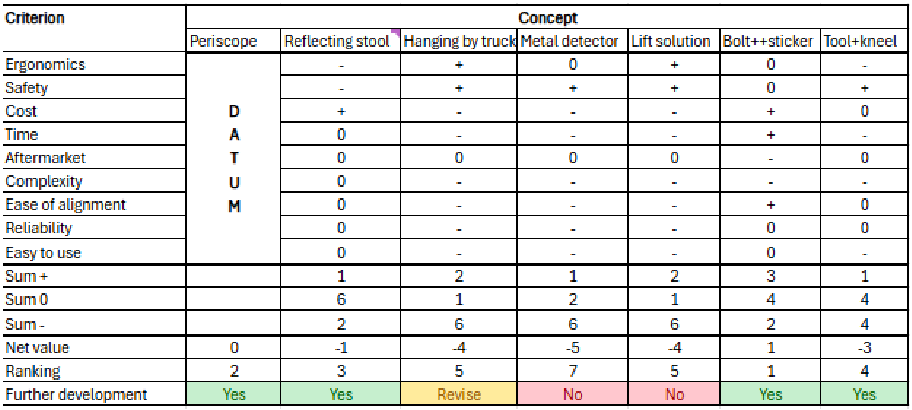
D

Appendix D-Selection matrices



Criterion	Concept						
	Tool+kneel	Reflecting stool	Hanging by truck	Metal detector	Lift solution	Bolt++sticker	Periscope
Ergonomics		+	+	+	+	+	+
Safety		-	+	+	+	0	0
Cost	D	+	-	-	0	+	+
Time	A	0	0	0	0	+	+
Aftermarket	T	0	0	0	0	-	0
Complexity	U	0	-	-	-	0	-
Ease of alignment	M	0	-	-	-	+	0
Reliability		0	-	-	-	0	0
Easy to use		0	-	0	-	+	+
Sum +		2	2	2	2	5	4
Sum 0		6	2	3	3	3	4
Sum -		1	5	4	4	1	1
Net value	0	1	-3	-2	-2	4	3
Ranking	4	3	7	5	5	1	2
Further development	Evaluate with a different reference						

Figure D.1: The first concept selection matrix, inspired by Ulrich et al. [3]



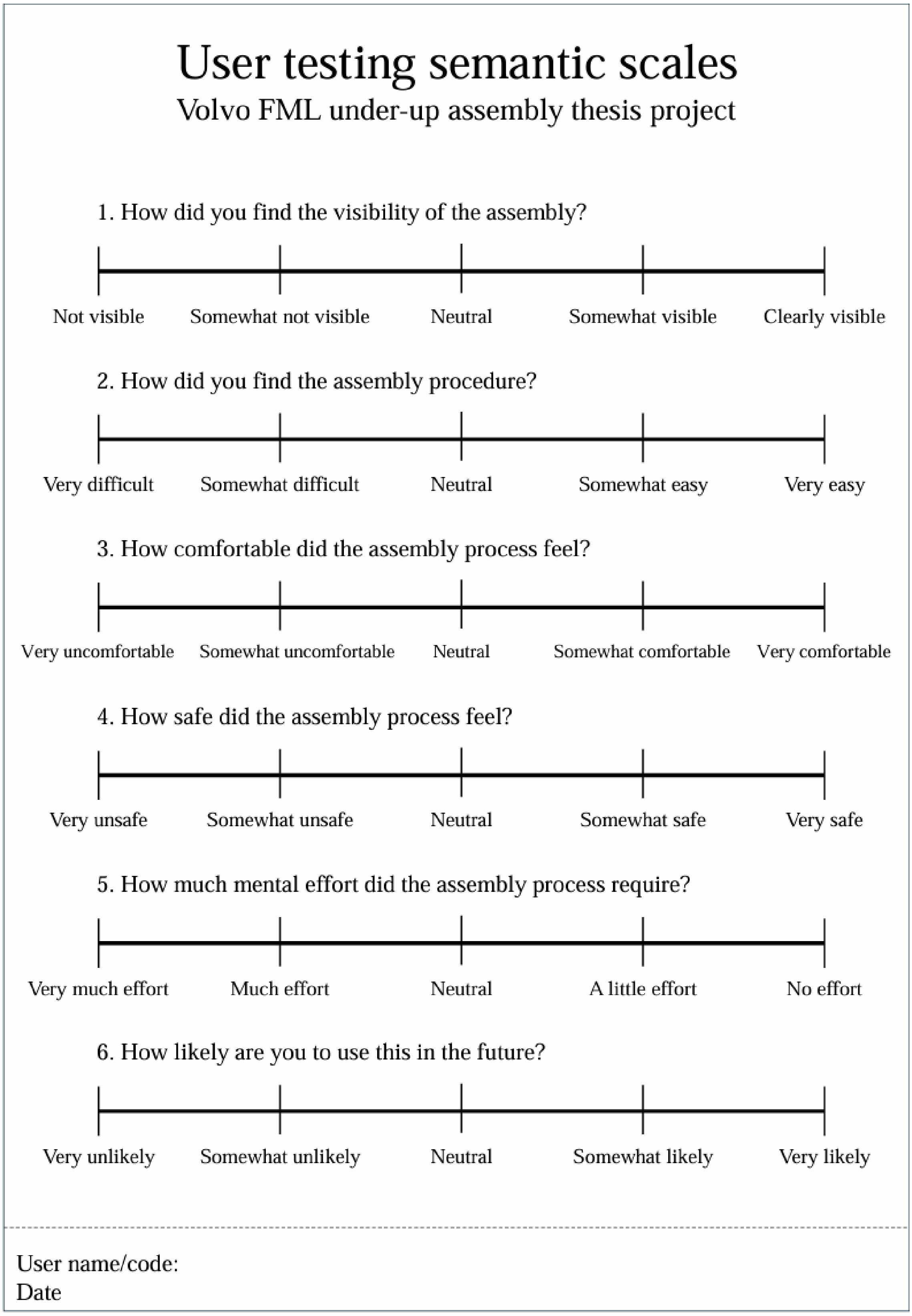
Criterion	Concept						
	Periscope	Reflecting stool	Hanging by truck	Metal detector	Lift solution	Bolt++sticker	Tool+kneel
Ergonomics		-	+	0	+	0	-
Safety		-	+	+	+	0	+
Cost	D	+	-	-	-	+	0
Time	A	0	-	-	-	+	-
Aftermarket	T	0	0	0	0	-	0
Complexity	U	0	-	-	-	-	-
Ease of alignment	M	0	-	-	-	+	0
Reliability		0	-	-	-	0	0
Easy to use		0	-	-	-	0	-
Sum +		1	2	1	2	3	1
Sum 0		6	1	2	1	4	4
Sum -		2	6	6	6	2	4
Net value	0	-1	-4	-5	-4	1	-3
Ranking	2	3	5	7	5	1	4
Further development	Yes	Yes	Revise	No	No	Yes	Yes

Figure D.2: The second concept selection matrix, inspired by Ulrich et al. [3]

E

Appendix E-User testing template

E.1 Semantic scales



User testing semantic scales

Volvo FML under-up assembly thesis project

1. How did you find the visibility of the assembly?

Not visible	Somewhat not visible	Neutral	Somewhat visible	Clearly visible

2. How did you find the assembly procedure?

Very difficult	Somewhat difficult	Neutral	Somewhat easy	Very easy

3. How comfortable did the assembly process feel?

Very uncomfortable	Somewhat uncomfortable	Neutral	Somewhat comfortable	Very comfortable

4. How safe did the assembly process feel?

Very unsafe	Somewhat unsafe	Neutral	Somewhat safe	Very safe

5. How much mental effort did the assembly process require?

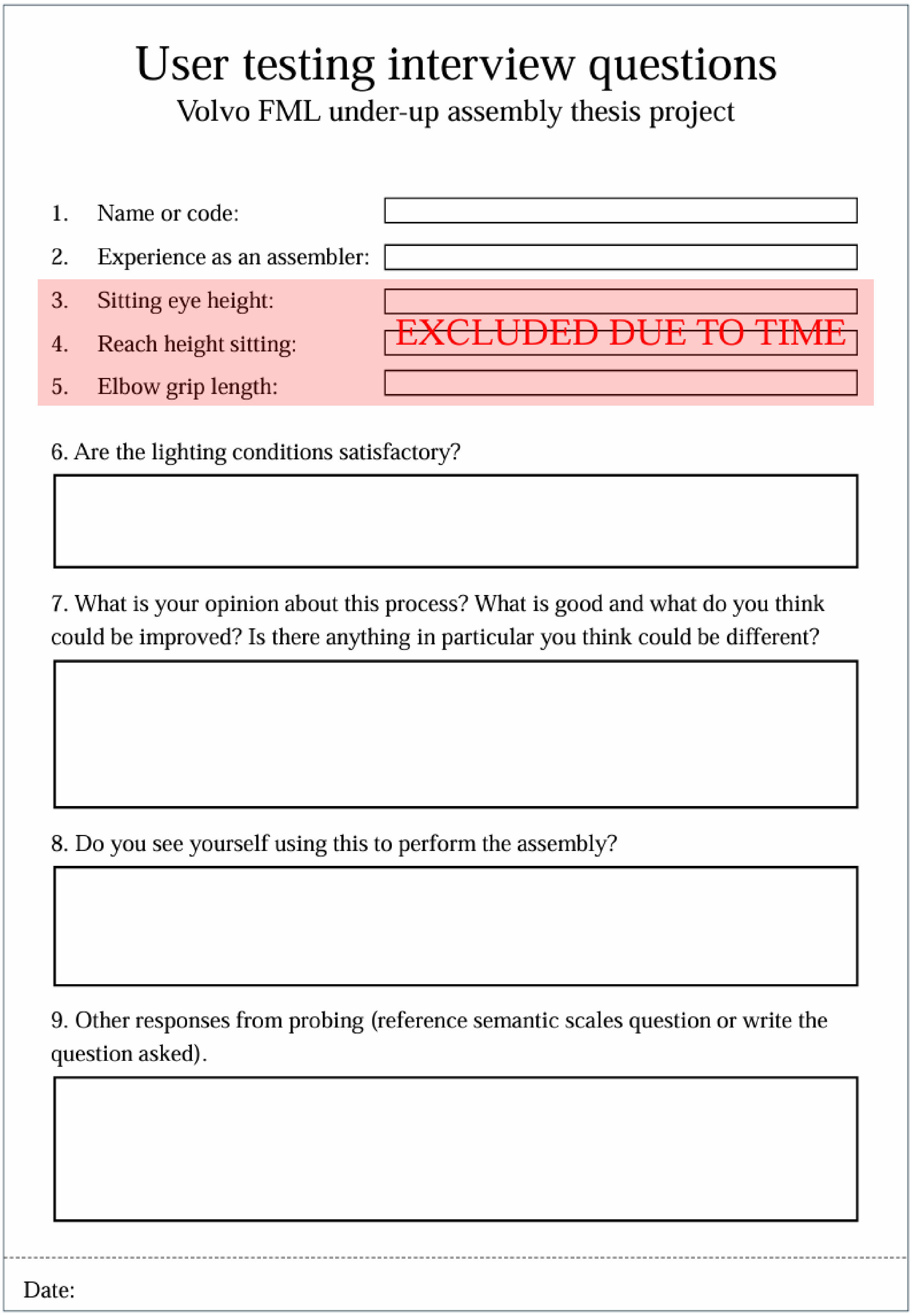
Very much effort	Much effort	Neutral	A little effort	No effort

6. How likely are you to use this in the future?

Very unlikely	Somewhat unlikely	Neutral	Somewhat likely	Very likely

User name/code:
Date

E.2 Interview questions



User testing interview questions

Volvo FML under-up assembly thesis project

1. Name or code:
2. Experience as an assembler:
3. Sitting eye height:
4. Reach height sitting:
5. Elbow grip length:

EXCLUDED DUE TO TIME

6. Are the lighting conditions satisfactory?

7. What is your opinion about this process? What is good and what do you think could be improved? Is there anything in particular you think could be different?

8. Do you see yourself using this to perform the assembly?

9. Other responses from probing (reference semantic scales question or write the question asked).

Date:

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