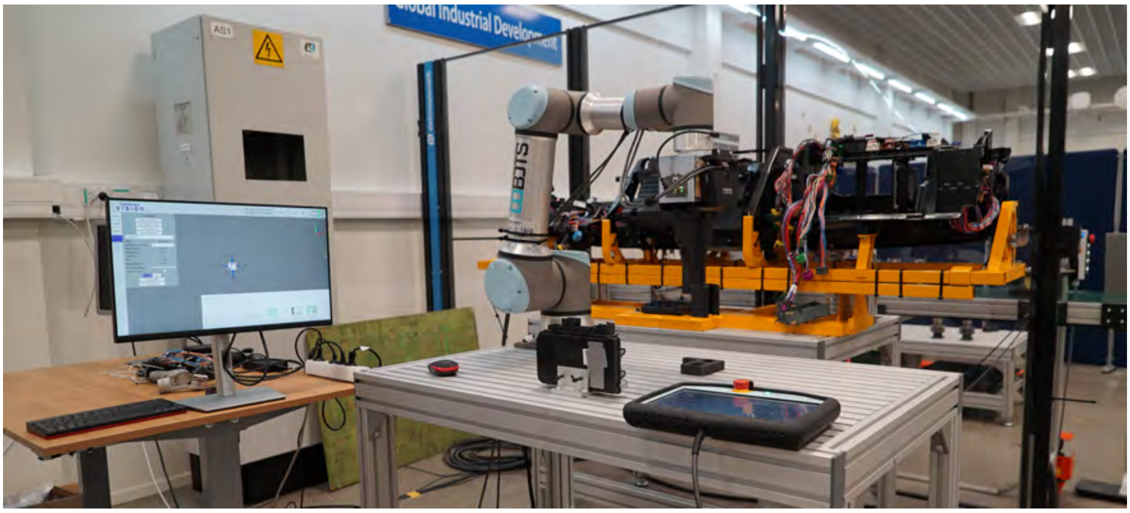

Automation of Connector Mating to Improve Wire Harness Assembly on Instrument Panel of Trucks

Master's thesis in Master of Science in Product Development

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CHALMERS UNIVERSITY OF TECHNOLOGY
Gothenburg, Sweden 2024
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Master's thesis 2024

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In collaboration with Scania Group

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Abstract

The assembly of wire harnesses in the automotive industry is predominantly a manual process that presents numerous ergonomic challenges, often resulting in musculoskeletal disorders among operators. One of the significant challenges in this assembly process is the mating of connectors. This thesis aims to automate the mating process to alleviate operator strain and enhance working conditions. This work is part of the Empowering Human Workers in Wire Harness Assembly (EWASS) project, in collaboration with Scania Group, Volvo Group, Volvo Cars, and academic partners including Chalmers University of Technology, University of Skövde, and Fraunhofer Chalmers for Industrial Mathematics (FCC). The research was conducted at the Smart Factory Lab at Scania Group. The focus of the experimentation was the instrument panel of the Scania truck, being manufactured at the Oskarshamn factory, due to identified ergonomic issues at the pre-assembly stations of the instrument panel.

A comprehensive study was conducted on current assembly procedures and automation technologies for wire harness assembly. The product development methodology was utilized, following the concept development funnel. Tools such as the function mean tree and morphological matrix were employed to generate concepts, which were then screened using elimination and Pugh matrices. The optimal concepts were further evaluated using the Kesselring matrix. The thesis culminates in the development of a functional setup capable of performing the connector mating process on the instrument panel, providing insights and learnings that can be applied to develop improved products for the automation of wire harness assembly.

Acknowledgements

First and foremost, we extend our deepest thanks to Fredrik Ore and Edgar Patzel, our supervisors at Scania. Their expert guidance, valuable feedback, and unwavering support were instrumental in shaping this work. We are also grateful to David Svensson, the manager of the Smart Factory Lab, for providing access to essential facilities and resources.

Special thanks are due to Johan Malmqvist, our supervisor and examiner at Chalmers University of Technology, for his insightful suggestions, thorough review, and constant motivation, which significantly enhanced the quality of this thesis.

We also thank all the individuals who participated in the interviews. Their willingness to share their experiences and perspectives was vital for the research findings. Our sincere appreciation goes to company Cambrian for their generous support and the materials they provided, without which this project could not have been completed.

Lastly, we extend our gratitude to everyone who supported us with the necessary equipment and tools during this thesis. Their contribution was crucial to the successful completion of this project. This work would not have been possible without these individuals' collective efforts and support.

Amir Rahmani, Harshit Singh, Gothenburg, June 2024

List of Acronyms

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

CA	Cable Assembly
Cobot/s	Collaborative Robot/s
ECU	Electrical Control Unit
HRC	Human Robot Collaboration
MSD	Musculoskeletal disorder
SES	Scania Ergonomic Standard
SFL	Smart Factory Lab
WH	Wire Harness
WHA	Wire Harness Assembly
BUMS	Belastningsergonomisk Utvärderingsmall Saab

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1

Introduction

The introduction chapter provides a comprehensive overview of the study, starting with the background and problem analysis that highlight the challenges in the current wire harness assembly processes. It then outlines the study's aim and research questions, discusses the limitations of the research, and provides an overview of the subsequent chapters in the report.

1.1 Background

Wire harnesses are an essential component used in various industries, particularly the automotive industry, for transmitting electrical signals and power throughout the different components of the product. The assembly of these wire harnesses is monotonous and involves a lot of strenuous manual labour. With the increase in electrification, the number of cables and connections is growing, increasing the probability of ergonomic injuries for the operators in factories.

The project Production2030 aims to strengthen the Swedish industry through collaboration between academia and industry. To improve ergonomics and achieve sustainable production, the project EWASS (Empowering Human Workers for Assembly of Wire Harnesses) was launched as a collaboration between Sweden-based universities and industrial companies (Produktion2030, 2022). This project aims to solve the challenges of incorporating modern technologies in the wire harness assembly like Human-robot collaboration and cable simulation tools to enable a sustainable work-life for the operators. Vinnova supports the project and collaborators include Scania Group, Volvo Group, and Volvo Cars, from the industry side and Chalmers University of Technology, University of Skövde, and Fraunhofer Chalmers for Industrial Mathematics (FCC) from the academic side (Produktion2030, 2022).

At Scania, the project is being conducted by the Smart Factory Lab (SFL). The lab was established in 2019 ("Smart Factory Lab", n.d.), with the miission of adapting, evaluating, sharing and delivering digitalisation and automation solutions ("Smart labs", n.d.). The focus of this project is on the automation and improvement of the cable assembly process for wiring harnesses by developing state-of-the-art solutions to alleviate the burden on operators, reduce monotony, and enhance overall productivity within the assembly line. This strategic move not only aligns with Scania's commitment to sustainability but also underscores its dedication to staying at the forefront of technological advancements in manufacturing. The instrument panel which sits in the cabin of the trucks was chosen as the problem to be solved for the wire harness assembly. The mating of connectors to the engine control units (ECUs) was identified as a significant ergonomic challenge in the assembly stations, as highlighted by the Scania ergonomic assessments. The panel is assembled in the Oskarshamn (Sweden) and Sao Bernardo (Brazil) factories of Scania where the cabin of the trucks are manufactured. It has a complex wire harness assembly process with multiple ECUs, each having multiple connections.

1.2 Problem Analysis

The instrument panel variant that was investigated in this case study was given to the Smart Factory lab by the Oskarshamn factory has four ECUs, each of them with an average of 3 connectors. There are 6 different types of connectors in the panel with 4 of them from the same family (having the same shape, only differing in the number of pins). Each connector requires a different amount of force to mate, reaching more than 100 newtons for some.

Currently, the mating of these connectors to the ECU is done manually by operators using their hands one by one. If individual connectors are particularly difficult to connect, a customised pliers tool is available. However, this tool is rarely used due to the additional handling effort involved. The operators mate the connectors to the ECU before fitting the ECU to the panel itself. From the statistics on injury from January 2022 to November 2023 on the assembly line of the instrument panel to the cabin in Oskarshamn, it is observed that around 50% of complaints were for hand-related injuries.

1.3 Aim & Research Questions

The thesis aims to study and develop methods and different approaches that incorporate automation for the mating of connectors in the wire harness assembly. This will allow the production and R&D departments to identify effective strategies for enhancing the working conditions for operators through improved assembly ergonomics.

As a part of the research planning process, a list of research questions was created to gain knowledge on the subject of wire harness assembly and its current automation level. As the wire harness assembly is a vast topic, these questions helped us keep a clear focus on the aspects relevant to the project's objectives and scope. By exploring these questions, necessary data to investigate the project's aim was gathered and to identify the significant results.

1. What are the challenges associated with implementing automation in wire harness assembly (WHA) process?

2. What technologies are being developed and explored for mating connectors in wire harness assembly?
3. What type of collaborative setup is most effective for the mating of connectors?
4. How should grippers be designed for robotic systems to effectively pick up connectors?
5. What design guidelines can be derived from the tests and experiments for products that include wire harnesses to facilitate the integration of automated wire harness assembly processes?

The thesis was open-ended, meaning that the final result is not confined to a single complete solution rather, multiple alternative solutions have been considered. Evaluation of these solutions primarily occurred in Scania's Smart Factory Lab, where prototypes were built, tested, and assessed. The objective was also to develop at least one functional setup capable of completing the connector mating process into the ECU.

1.4 Limitations

Wire Harness Assembly (WHA) is a process employed in multiple different parts of Scania trucks e.g. chassis, battery packs, etc. but due to restriction of the project period and resources available focus will be on the mating of connectors in the assembly of the instrument panel located in the cabin of the truck. In the instrument panel, various types of Electronic Control Units (ECUs) are installed, each equipped with different variants of connectors. Consequently, the thesis will prioritise one family of connectors with the highest mating force, irrespective of the ECU.

The UR16e, a collaborative robot from Universal Robots (Robots, n.d.) was chosen as the automation tool for the thesis, as it was available to be tested in the lab. Universal Robots offer a node-based programming system with a graphical user interface that can be accessed using the robot's pendant. Other robots were not considered for the prototype and testing given the time constraints for the thesis.

Although the station on which the ECU is assembled is on a continuously driven assembly line, to limit the problem scope to the focus of the assembly of cables, it was decided to use a stationary testing position. The fixture on the actual production line can also be can be manually rotated and adjusted in height for the operator, however, this was not implemented in the test setup for the thesis.

Despite the substantial costs associated with the concept, it was not given a lot of consideration, as the thesis is research-based and the aim was to develop and test multiple concepts. Though, due to resource limitations within SFL and time considerations for certain components, some experiments could not be conducted for a few concepts.

1.5 Outline of the Report

The first chapter of this thesis report will be the Introduction, followed by the Research Approach, State of Art, Results, Discussion, and Conclusion.

The Introduction chapter will provide background information on the problem and outline the research questions to be investigated in this thesis. The Research Approach will explain the methodologies that will be used in this report to achieve results. The State of Art section will elucidate existing solutions and technologies thus far. The Results section will describe the various steps undertaken during the thesis and what was accomplished as a result. The Discussion chapter will answer and discuss the research questions and provide reflection on the entire process. The Conclusion chapter will focus on future work.

2

Research Approach

This chapter outlines the research approach adopted for the master's thesis following a structured process from project planning to the exploitation plan.

2.1 Overall Research Process

The product development process that will be implemented in this thesis is largely inspired by the book Product Design and Development written by Ulrich et al., 2019. With inspiration from the aforementioned book and according to factors such as time restriction of the work, goals and the conditions of the execution of the development process, a diagram of the entire process was compiled, seen in Figure 2.1. The process was divided into five parts, starting with the project planning phase, identifying the customer needs, concept generation, screening, evaluation and then generating the evaluation plan.

During the development of the product, a simple agile project management process was implemented. Given the project's evolving nature and broad scope, which required adjustments based on experimentation time and available equipment, an agile approach was deemed suitable. Agile methodology, known for its flexibility and iterative nature, allowed for quick adoption to changes and integration of continuous feedback. This approach facilitated regular reassessment of priorities and goals, ensuring that the project remained aligned with user needs and project constraints. A simple sprint was set up with a duration of one week. The team met with the supervisors from Scania, every week to relay to them the tasks accomplished within the week and the agenda for the next week and to receive feedback.

Throughout the concept development phase, the test-design-build strategy from lean product development was used (Raudberget & Gustafsson, 2012). This approach emphasises on rapid iteration and continuous improvement, which was crucial for a research thesis with a wide scope. This method also claims to be more efficient and reduce waste in projects. After the initial iteration of the concept was ready, it was tested to gather feedback and identify potential problems. Insights from this step are then used in the design process of the new iteration and then the new prototypes are built. This cycle of testing, redesigning, and building continues until the product meets all desired criteria.

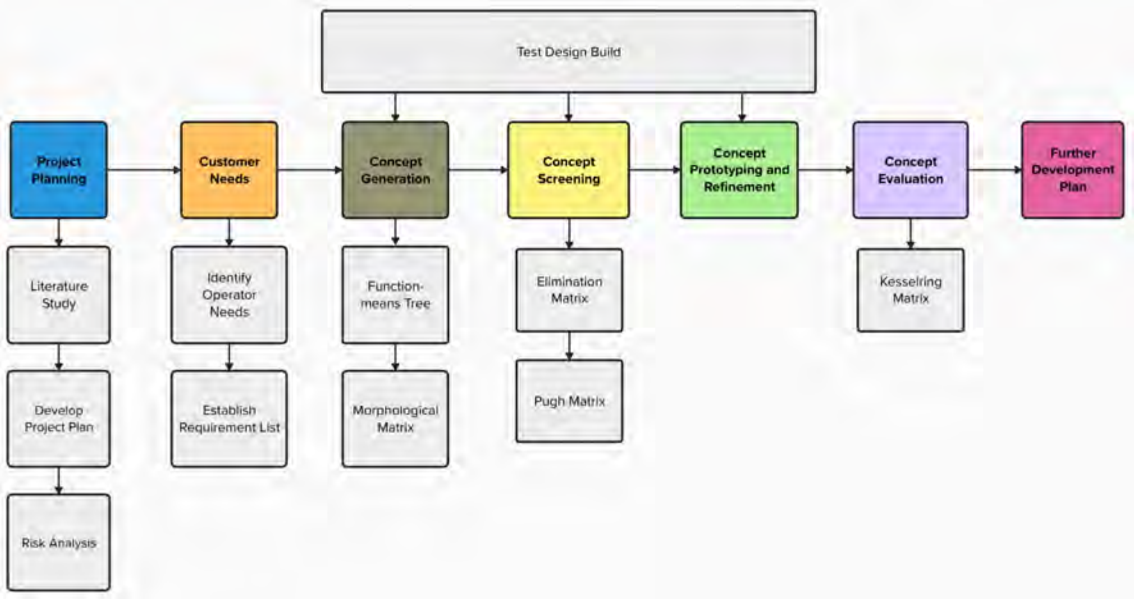


Figure 2.1: Research Process

2.2 Project Planning

This phase is a critical foundation of the entire concept development process. It is essential to define the direction of the project and ensure the alignment of the project objective with the tasks that will be performed.

2.2.1 Literature Study

This initial step involves conducting holistic research on the problem and the wire harness industry. This step was used to collect data on research questions 1 to 3 that focus on finding the current status of cable assembly and automation in connector mating on the Scania assembly line at Oskarshamn and in the industry in general.

The primary objective of conducting this literature study was to understand the current status of the industry in regard to cable assembly automation, with a particular emphasis on the mating of connectors. This involved exploring the latest technological advancements, identifying industry best practices, and examining the challenges and opportunities associated with implementing automation in this context. By examining the work of previous researchers and practitioners, the literature study not only identified gaps in existing knowledge but also uncovered best practices and highlighted emerging trends and technologies that informed the project's development.

2.2.2 Develop Project Plan

Based on the insights gained from the research, the next step was to develop a detailed project plan. This plan acted as a roadmap that guided the project through the various stages of development. The project plan began with clearly defining the project aim and scope, detailing the primary objectives and research questions. This included specifying the key deliverables and outlining the limitations that could impact the project's execution.

To ensure that these deliverables were achieved on time, a detailed timeline was created using a Gantt chart, mapping out each phase of the project from initial research and concept development through final testing. This timeline included all major milestones, deadlines and activities providing a clear schedule to follow.

2.2.3 Risk Analysis

To mitigate risks and their potential consequences, a comprehensive risk analysis of the project was conducted. Each risk was assessed by determining its likelihood of occurrence, ranging from less than 5% probability (1) to over 80% probability (5), and its impact on the project's interim goals and planning, also rated on a scale of 1 to 5. The overall risk score for each identified risk was calculated as the product of its probability and impact ratings. Based on these scores, specific actions were recommended to address and manage the risks, detailed in A.1.

2.3 Customer Needs

This phase aims to capture and understand the needs of customers, which in this project relate to the operators of the assembly of cable harnesses. It is fundamental to ensure that the project aligns with the expectations of the operators and other stakeholders involved.

2.3.1 Identifying Operator Needs

The initial step in this phase involved identifying the specific needs of the operators who will be using the station. This was achieved through a combination of qualitative and quantitative research methods, designed to gather comprehensive insights into preferences and pain points.

For quantitative research, the objective was to gather data from the assembly stations, like the assembly process, forces involved in the assembly process, and the ratings of the station according to the Scania Ergonomic assessments (SES).

For qualitative research, semi-structured interviews were conducted with operators, academic researchers, and industry professionals to derive a detailed overview of the problems associated with cable assembly and difficulties in its automation and the current automation techniques in research for cable assembly and deriving the operator needs from it.

2.3.2 Establish Requirement List

After detailed research and identifying the operator and other stakeholder needs, the requirement list was developed. This list is a translation the qualitative needs to quantifiable and evaluable criteria, ensuring that the final product will address the identified preferences. Additionally, the list includes performance metrics and benchmarks that are crucial for the product's evaluation during the testing phase. These metrics ensure that the product not only meets the basic user needs but also performs reliably and consistently under various conditions.

The requirements were systematically categorised into various groups such as ergonomics, automation and productivity to simplify evaluation. Each requirement is classified either as a desire (D) or a requirement (R). For each criterion, a target value is established to serve as a benchmark for assessing the product's performance and functionality. These values act as reference points to determine how well the product meets the specified criteria. Additionally, there is a column detailing the methods for evaluating and verifying each requirement. To further enhance the management of these requirements, a column indicating their relative importance is included, with a scale from 1 to 5, 1 signifying the lowest priority and 5 the highest priority.

2.4 Concept Generation

This phase is the stage where the initial ideas are transformed into tangible product concepts. According to Ulrich et al., 2019, this phase involves generating, evaluating and refining potential solutions that solve the original problem while meeting the identified customer needs.

2.4.1 Function Means Tree

A function means a tree is a tool used to decompose the problem into functions and then generate concepts using those functions. It works on the concept of function analysis, which involves dividing the main function of the product into various sub-functions that can be managed more easily (Ulrich et al., 2019).

The tree is a hierarchical representation that connects each primary function to its various means or solutions that can fulfil it. The function means tree was used to identify the important functions involved in the mating of a connector in a cable harness assembly process.

2.4.2 Morphological Matrix

After the sub-functions were identified, a brainstorming session was used to generate concepts that could solve them. In this step, the practicality of the idea was not considered, instead the focus was to come up with as many ideas as possible, to have a broad spectrum of ideas. Sketches and role-playing were used to explain the idea to other stakeholders for their opinions.

After having multiple concepts for each sub-function, a morphological matrix was formed combining all of the ideas in one matrix. The morphological matrix, similar to the Concept Combination Table in Ulrich et al., 2019 is a tool used generally in the concept development phase to consider all possible solutions to the problem in an easy and intelligible style. The matrix arranges the solutions in systematic organisation by listing the functions on one axis and all the possible means to achieve those functions along the other. This allows a structured exploration of potential design combinations. By analysing these combinations, the most promising concepts can be identified to develop a concept catalogue.

2.5 Concept Screening

Concept screening is the step in the product development process where the initial concepts generated by the morphological matrix are evaluated to identify the most promising concepts for further development. This phase involves a systematic assessment of each concept against predefined criteria from the requirement list developed from the customer needs. For this thesis, the Elimination matrix and Pugh matrix were used for the screening process.

2.5.1 Elimination Matrix

After a concept catalogue was made, the first screening process used was the elimination matrix. The elimination matrix is used early on in the screening process to remove the less viable ideas early in the evaluation process. The concepts were evaluated as pass/fail for each criterion, which is taken from the requirement list developed. This is a relatively quick process, taking into consideration only the important criteria that need to be met for the project. This was used to narrow down a large array of initial concepts, which would be difficult to evaluate with other techniques.

2.5.2 Pugh Matrix

The Pugh matrix, developed by Stuart Pugh in the 1980s, is the recommended method for concept screening in the Ulrich et al., 2019. It facilitates the comparison of all the remaining concepts with each other using a set of criteria taken again from the requirement list. The process involves selecting a reference concept, and then rating other concepts against this reference across various criteria. A '+' is used if the concept is better than the reference concept for that criterion, if it is worse a '-' is used instead. If the concepts are considered similar to each other for the criterion then a '0' is used as the rating. After all the concepts have been rated for all the criteria, a sum of all the '+','-' and '0' gives out the final score for each concept. Using this final score, a ranking of all the concepts can be done. If the number of concepts still have to be decreased, another iteration of the matrix can be performed by eliminating lower ranking concepts, changing the reference concept, combining concepts and by adding or removing criteria.

2.6 Concept Prototyping and Refinement

This phase of the process is where the final concept catalogue from the Pugh matrix is taken and developed into tangible physical concepts. The concepts are also iteratively improved based on observation and feedback. This step ensures that the selected concepts are aligned with the user needs and provides a view of how the concept will fare in the real world application and help in identifying new problems and technical constraints.

After the initial concept screening, the most promising concepts were developed into prototypes. The setup being developed has multiple after-market parts, but the prototyping techniques of 3D CAD modelling, physical mock-up and 3D printing were used to have the complete setup. For this step, a lot of limitations needed to taken into account which are explained in 1.4.

During the development of the final concepts, as explained before, the test-design-build strategy was employed. Before making the whole setup, the concepts were first tested for individual functions in a smaller setup to validate their feasibility. This approach allowed early detection and resolution of issues. By the end of this phase, a prototype for each concept to be vetted had been developed.

2.7 Concept Evaluation

Once the final concepts were prototyped, they need to be evaluated to determine their feasibility and alignment with the goals of the project. This evaluation was done using the Kesselring matrix.

2.7.1 Kesselring Matrix

The Kesselring matrix, similar to the concept scoring matrix in Ulrich et al., 2019, is a method used to evaluate the concepts against the most ideal concept based on multiple criteria. It is a more polished approach to concept evaluation than a Pugh matrix.

Each criterion is assigned weights to them based on their importance. The concepts are then scored against these criteria within a defined range, which is selected as 1 to 5 for this thesis, of which the ideal concept that has the best value for each criterion. After the scoring of each concept, the scores are multiplied by the weights for each criterion to get a weighted score of the concept for that criterion. These weighted scores are then added up to have a final score for the concept. These final scores are then used to get the final rank of the concepts.

To develop the weights for the criteria, a pairwise comparison matrix is used. Each criteria are compared against each other on the basis of their importance and relevance for the project. The scale for comparison is given as '0' if the criterion in the row is less important than the criterion in the column, '0.5' if the criterion in the row is as important as the criterion in the column, and 1 if the criterion in the row is more important than the criterion in the column. The total sum of the row is calculated providing a sum for each criterion. To find the weights, a relative sum for the criterion is calculated by by dividing the sum of the criterion by the total sum of all criteria.

2.8 Further Development Plan

A further development plan is a strategic approach designed to build upon the results and outputs of the project. It details how the findings can be utilised for future advancements of the project. For this thesis, the plan includes potential future work and directions that can build upon the current research.

3

State of Art

The State of the Art chapter gives an introduction to wire harness and wire harness assembly. It also explores how the assembly process of the instrument panel is done at the Scania factory with an introduction to the Scania Ergonomic Standards and the results of the assessments on the assembly stations. It is concluded by a literature review that explores the existing methodologies, technologies, and advancements in the field of wire harness assembly, with a specific focus on automation.

3.1 Wire Harness and Wire Harness Assembly

This section explores the wire harness industry and the wire harness assembly process in general automotive industry and then entails how the assembly is done in the Oskarshamn factory of Scania.

3.1.1 Wire Harness

Wire harness is a crucial component in modern electrical systems in across various industries like automotive, aerospace and telecommunications. It is a composition of electrical connectors, cables, fuses, and switching boxes that are meant to connect sensors, batteries, electronic control units and any other electronic components to each other (Navas-Reascos et al., 2023; Synopsys, n.d.).

It is a specially significant in automotive industry, as it is already the most expensive and complex individual electrical component in vehicles, which can be seen in Figure 3.1 (Heisler et al., 2020). The harness is a pivotal link within the E/E (electrical/-electronic) system that transfers energy and information, enabling functions such as steering, braking, and infotainment (Nguyen et al., 2020). With the shift towards electrification and automation of vehicles, the length and complexity of these harnesses are increasing in addition to their heightened importance in the overall vehicle assembly. For instance, the length of a wire harness in a passenger car has increased from $1000m$ in the year 2000 to $2800m$ in year 2020, with increase in variation and number of components in the harness at the same time (Wang et al., 2023). The market size for the automotive wire harness is expected to increase exponentially and reach USD 74.46 billion by 2030, (Salunkhe, Quadrini, et al., 2023).

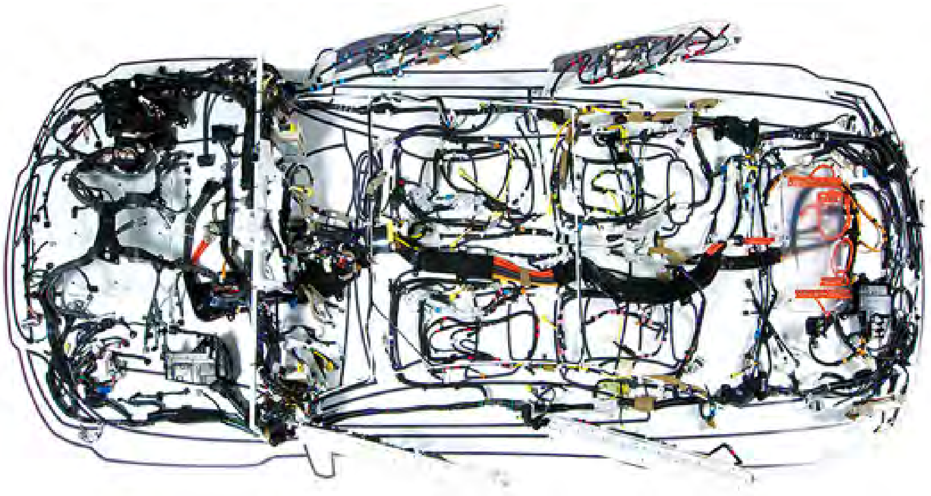


Figure 3.1: Example of a wire harness in a car (Yazaki, n.d.)

3.1.2 Wire Harness Assembly

Wire harness assembly (WHA) with respect to the automotive industry, is the act of assembling the wire harness package received from the supplier on the product, i.e. mating all the connectors, terminals, fuses and other E/E components to their designated positions along with securing the harness to the product.

Wire harnesses can vary significantly in sizes, ranging from small, intricate configurations to larger, more complex arrangements. This variation along with the tendency of wire harnesses to be very flexible necessitates the assembly to be manual. However, the manual nature of this assembly process presents considerable strain and ergonomic challenges for operators, as they must navigate through the intricate network of wires and connectors to ensure precise and accurate assembly (Heisler et al., 2020). This assembly process highly increases the risks of musculoskeletal disorders in the operators working on the stations, due to the inherently labour-intensive, repetitively handle and manipulate wires, connectors, and other components putting strain on their muscles and joints (Salunkhe, Quadrini, et al., 2023).

3.1.3 Wire Harness Assembly at the instrument panel pre-assembly line in Oskarshamn

The wire harness assembly process studied for this thesis is done at a pre-assembly line at the Oskarshamn factory of Scania. The pre-assembly involves the assembly of the wire harness to the instrument panel as well as other components. After the completion of the pre-assembly, the instrument panel is assembled in the cabin of the truck. It is a continuous moving line that moves at a constant speed. The steps performed by the operators on a span of multiple stations is similar to the assembly operation shown in (Salunkhe, Stahre, et al., 2023) of the wire harness assembly at the Volvo Cars' final assembly plants. The steps that are performed on the line across multiple stations are as follows:

1. Lift the wire harness package received from the supplier on a table and unpack it.
2. Load the wire harness onto a transport cart.
3. Take the cart to the assembly station.
4. Unload the wire harness from the cart and arrange it on the instrument panel as instructed.
5. Attach the connectors to their respective ECUs and fit the ECUs on the panel in the designated positions, again as instructed by the element sheets.
6. The wire harness is then permanently fixed to the panel using clips and cable ties. Some of these fixing are also done while assembling the ECU's.
7. A visual check is performed to inspect if the assembly is accurate and free from any defects or discrepancies, ensuring the integrity and functionality of the wire harness system.

The assembly is particularly challenging as Scania manufactures all the truck variations on the same line. This leads to high variance in the instrument panel wire harnesses as the panel and the ECUs that are on it, are directly affected by the type of truck and also the modifications that the customer has chosen.

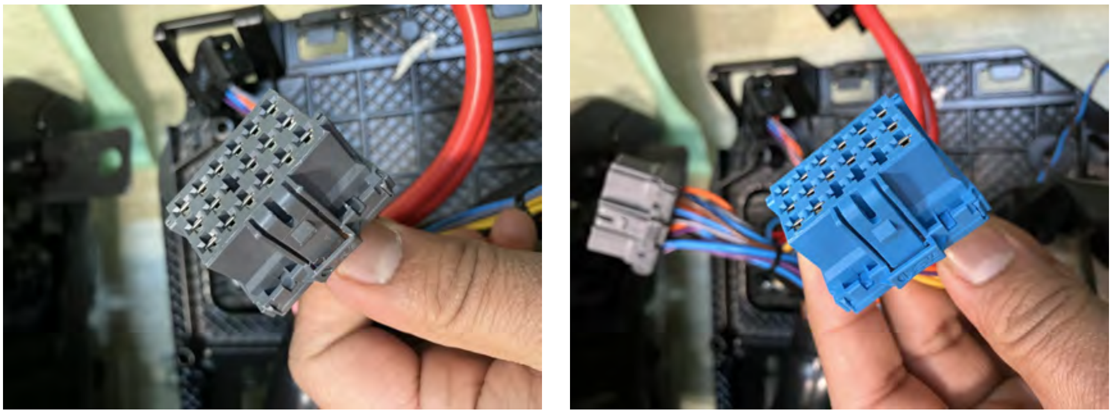
3.2 ECU & ECU connectors

ECU is a device that is used to control a specific function on the vehicle. Vehicles today are really complex and can have a lot of ECU's at the same time. These act as the brain of the vehicle regulating important functions like steering, engine, HVAC, braking etc. They also control passive functions of safety features as airbags, etc (APTIV, 2020).

The instrument panel that has been set up in the SFL, provided by the Oskarshamn factory, for experimentation contains four ECU's. These ECUs are designed by Scania but the manufacturing of the ECU and the connectors along with the wire harness is done by the supplier. One ECU, the CUV3, is on the left side of the panel, attached to it on a bracket using a screw. The rest of the three ECUs are placed on the right side of the panel in an ECU compartment where they are fitted with snap fits. There are in total 13 connectors that mate with the ECUs. The number of wires installed in the connector varies depending on the functionality to be fulfilled precisely in the predetermined specification of that truck model.

Figure 3.2: ECU assembled to the instrument panel with 4 connected cables

The ECU CUV3 is on the left side of the panel, attached to it on a bracket using a screw. It has four connectors, each different from the other. The ECU can be seen in Figure 3.2 with all the connectors attached to it on the instrument panel. As seen, it is fixed on the instrument panel on a bracket that is welded to the panel. One of the connectors has a lever-shaped housing that is used for a more ergonomic mating of the connector. This housing lowers the force required for pressing the connector into the socket. The grey and the blue connector as seen in Figure 4.6 are similar to each other in shape with the only difference being the guiding extrusions ("6-968974-1 : AMP Automotive Housings", n.d.; "8-968974-1 : AMP Automotive Housings", n.d.). These connectors have the highest joining force required amongst other connectors in the ECU.



(a) Grey Connector

(b) Blue Connector

Figure 3.3: Connectors on the ECU CUV3

3.3 Scania Ergonomic Standard (SES) and station assessments

This section details the Scania ergonomic standard, its different types and how it is used to evaluate and improve ergonomics throughout the whole product development process. It also entails the evaluations that the thesis will focus on with the results from the stations where the ECU are assembled.

3.3.1 Scania Ergonomic Standard (SES)

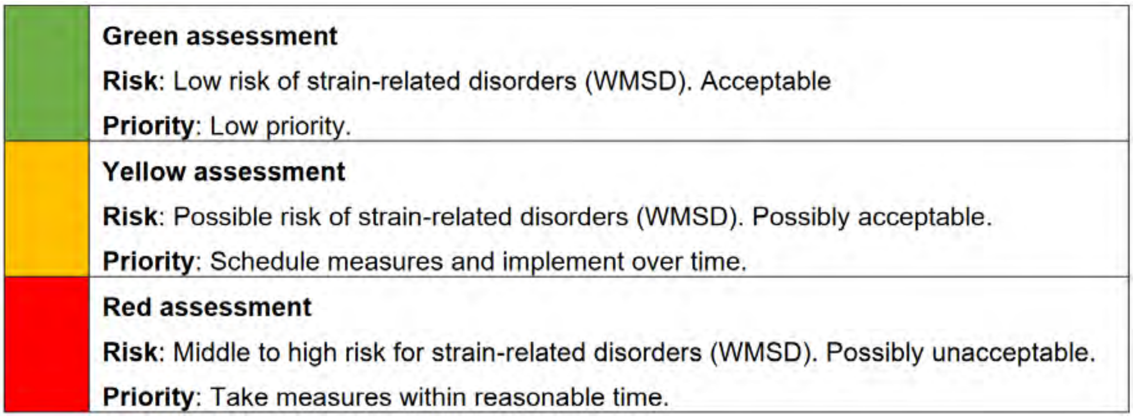
SES is a framework that Scania has developed to evaluate ergonomics within the production to keep standard measurements throughout the company. There are three main SES standards, SES Design, SES Assembly and SES RAMP (Risk management Assessment tool for Manual handling Proactively).

SES Design is used for assessment of the new design solutions. It has its roots in Belastningsergonomisk Utvärderingsmall Saab (BUMS) (Bašić & Idoffsson, 2016). The aim of this assessment is to evaluate products in their design stage before they are put into manufacturing and in the production line. In this way, the components can be influenced early on in their design phase to improve their ergonomics, reducing the risk of MSD's for employees.

SES Assembly also has its origins in BUMS adopted for Scania. It is used to pinpoint ergonomic problems in an existing production flow within a factory setting. It is especially useful for ergonomic assessments on the number of work cycles that could cause strain in the long term. This assessment is generally done per station on the line, or for tasks with tact times not more than ten minutes. These evaluations can be used for the development of simple tools to solve the ergonomic problem or it can even lead to expensive machine investments if necessary.

SES RAMP was developed with KTH to evaluate the risk assessment of manual work and load for the entire working day. This could involve manual handling, lifting, pushing or pulling a load manually. It is used as an assessment tool for tasks such as packaging, material loading and unloading, etc. It is generally based on an average working day instead of a short sequence of tact time. It also takes into account variations in work tasks that are not done by either of the other assessments.

Almost all the assessments for the SES standards are divided into three groups, green, yellow and red that are assigned specific values given the evaluation criterion. Green represents low risk of ergonomic hazards that is on low priority zone, yellow represents possible risk of disorders, but improvement measures can be taken over time and red represents high risks of hazard that need to solved within reasonably quick time. SES Design and SES Assembly also have a risk assessment of DRV (Double red value), which represents very high risk of disorders for the operators, and there should be an immediate action taken to solve the issue. Figure 3.4 shows the assessment groups for SES Assembly (Viktorsson et al., 2023).



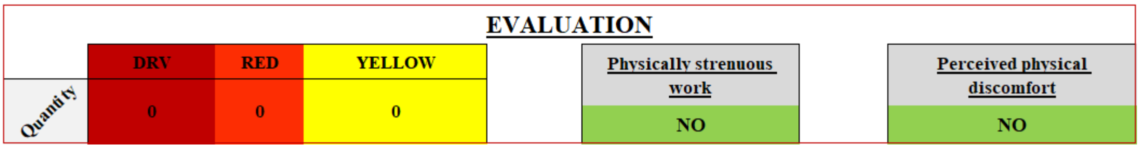
🟩	**Green assessment** **Risk**: Low risk of strain-related disorders (WMSD). Acceptable **Priority**: Low priority.
🟨	**Yellow assessment** **Risk**: Possible risk of strain-related disorders (WMSD). Possibly acceptable. **Priority**: Schedule measures and implement over time.
🟥	**Red assessment** **Risk**: Middle to high risk for strain-related disorders (WMSD). Possibly unacceptable. **Priority**: Take measures within reasonable time.

Figure 3.4: Assessment groups for SES Assembly (Viktorsson et al., 2023)

3.3.2 SES Assembly Criteria

For this thesis, only the SES Assembly is considered for evaluation and studies for the ergonomics of the station where the ECU is being assembled have been the objective. The station dedicated to ECU assembly takes centre stage in this analysis, reflecting a deliberate effort to reduce ergonomic challenges caused due to mating of connectors. The overarching objective is to systematically investigate and address ergonomic concerns within the station, aiming to optimise working conditions and minimise the risk of strain-related injuries for workers through automation.

The SES Assembly evaluates the stations along the assembly line using 21 criteria that are designed to identify ergonomic problems in a quantifiable way. These criteria evaluate tasks based on the repetition of movements, work postures, lifting requirements, and energy expenditure. These criteria are given a green, yellow, or red value, and sometimes a DRV as explained before. After individual evaluations, the final result are illustrated as seen in Figure 3.5 in a clear and distinct manner to identify the stations that need to be targeted for improvement.



EVALUATION

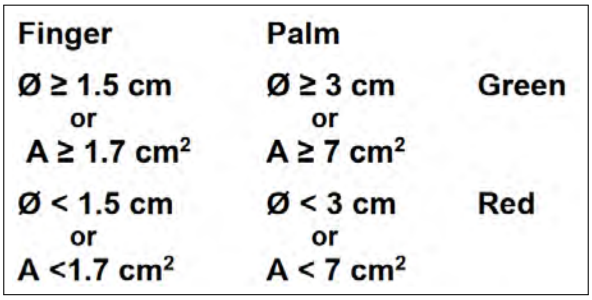
	DRV	RED	YELLOW	Physically strenuous work	Perceived physical discomfort
Quantity	0	0	0	NO	NO

Figure 3.5: SES Assembly evaluation result template (Viktorsson et al., 2023)

Some of the criteria that were focused on in this thesis are surface area for pressure, wrist positions and pushing/pulling with fingers, etc. because these were the problems identified on the SES assembly assessment on the stations discussed further in section 3.3.3.

The criteria nd their assessment values:

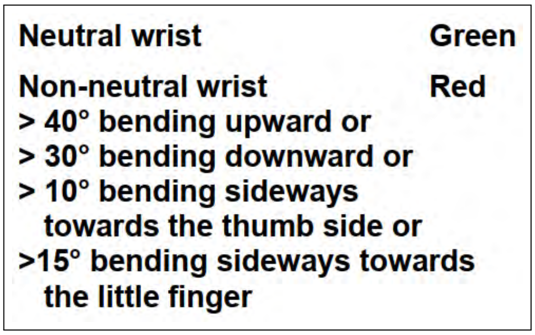
1. Surface area for pressure $\geq 10N$
   A substantial force on a limited area of contact can lead to significant strains on the body parts. These could also lead to musculoskeletal disorders. The assembly can also be difficult to perform effectively if the operator struggles to provide high-intensity forces on small surface areas. This is measured as the surface area on which the pressure is greater than $10N$. The assessment of the area for the finger and palm is shown in Figure 3.6. When the pressure is less than $10N$ the assessment is considered green.



Finger	Palm	
Ø ≥ 1.5 cm or A ≥ 1.7 cm^2	Ø ≥ 3 cm or A ≥ 7 cm^2	Green
Ø < 1.5 cm or A <1.7 cm^2	Ø < 3 cm or A < 7 cm^2	Red

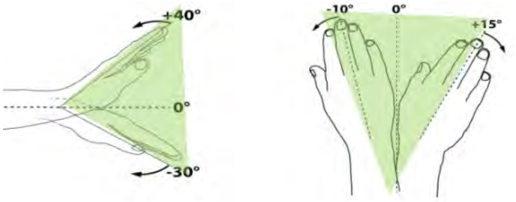
Figure 3.6: Assessment criteria for Finger and Palm (Viktorsson et al., 2023)

2. Static work posture for wrist ≥ 5 seconds
   The cartilage on the wrist is meant to both protect and lubricate the joint. It is more resilient in the centre of the joint and the weakest at the outer edges. Operating the wrist beyond the given limits for more than 5 seconds will also restrict the ability of operator their maximum grip. The wrist posture is checked for a cycle or a process. The duration of all periods lasting more than 5 seconds is totalled to find the cumulative duration of the static posture. A posture is considered static if the work posture is not changed for a minimum of 5 seconds. The assessment for the static wrist positions is shown in Figure 3.7.



Neutral wrist	**Green**
Non-neutral wrist **> 40° bending upward or** **> 30° bending downward or** **> 10° bending sideways towards the thumb side or** **>15° bending sideways towards the little finger**	**Red**

(a) Static Wrist Assessment values

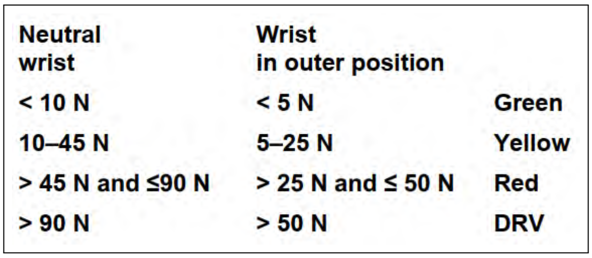


(b) Limit illustration of acceptable wrist positions

Figure 3.7: Static Wrist Assessment (Viktorsson et al., 2023)

3. Pushing, squeezing, pulling with fingers
   This criterion is the most valuable for the thesis, as it provides a direct evaluation point for the most troublesome step for mating of connectors, i.e. pushing the connector inside the socket. In the SES Assembly, this criterion is assessed

again, based on the wrist position as the wrist in outer positions can reduce the operator's force capacity by 50%. The assessment values can be seen in Figure 3.8.



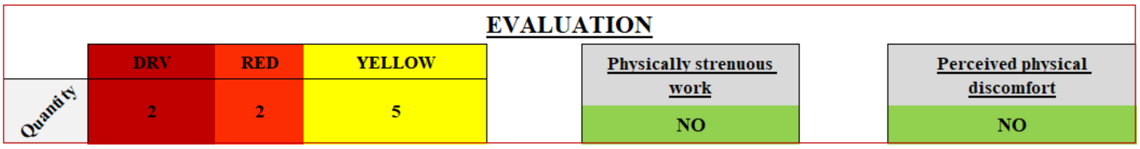
Neutral wrist	Wrist in outer position	
< 10 N	< 5 N	Green
10–45 N	5–25 N	Yellow
> 45 N and ≤90 N	> 25 N and ≤ 50 N	Red
> 90 N	> 50 N	DRV

Figure 3.8: Assessment Values for Pushing, pulling and squeezing (Viktorsson et al., 2023)

3.3.3 SES Assembly Assessment on Assembly Stations

The ECU CUV3 (assume Station A) and the other three ECU's (assume Station B) are assembled at different stations. A SES assembly assessment for these assembly stations have been conducted. The final result for the station A is shown in Figure 3.9 and for station B is seen in Figure 3.10.

Only some of the tasks in station A relate to the installation of the connectors in the CUV3 which is then mounted on the instrument panel. According to the ergonomic assessment as seen in 3.9, five yellow, two red and two DRVs have been identified. According to the assessment made, two of the criteria concern the mating of the connectors in CUV3. One is marked red, which indicates that the surface area where the force is more than $10N$ is less than 1.7 cm^2. This is because the undercut surface is not within the standard limits for finger pressure. The second criterion, marked with an DRV, concerns the push of the connectors with the appropriate force. This is because it takes more than 240 N with a neutral wrist and more than 120 N for a wrist in an extreme position to pair a connector with CUV3.



EVALUATION

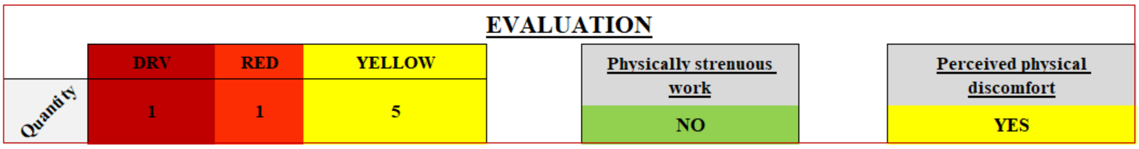
	DRV	RED	YELLOW
Quantity	2	2	5

Physically strenuous work	Perceived physical discomfort
NO	NO

Figure 3.9: SES Assembly Assessment Result Station A (Dolk & Karlsson, 2023)

The three ECUs being assembled on station B are fixed in place using snap fits, where the ECU has a cantilever extrusion design on the top and the bottom, which bends and fits into the slots. Just like for the previous CUV3 ECU, the connectors in these ECUs are mated before they are assembled on the instrument panel. Figure 3.10 shows the assessment result of station B where the ECUs are assembled. The station has five yellow, one red and one DRV. Out of these, one yellow, one red and one DRV are caused by mating of connectors on the ECU. The yellow is for the criterion of push / pull force in the hand or arm, which is between 20 to 45 N.

The wrist static position at the station is more than 5 seconds, which leads to a red value. Finally, the DRV was concerning the push of the connectors with more than $120N$ with a non-neutral wrist and $240N$ for a neutrally positioned wrist.



EVALUATION

	DRV	RED	YELLOW
Quantity	1	1	5

Physically strenuous work	Perceived physical discomfort
NO	YES

Figure 3.10: SES Assembly Assessment Station B (Karlsson & Dolk, 2023)

3.4 Human-Robot Collaboration

Human-robot collaboration (HRC) term represents an interaction between humans and robots to accomplish a task collaboratively. These systems do not have a physical safety barrier between humans and robots on the manufacturing floor. It is considered one of the main research topics for Industry 4.0, with increasing research on methodologies and technologies that improve HRC (Ajoudani et al., 2018).

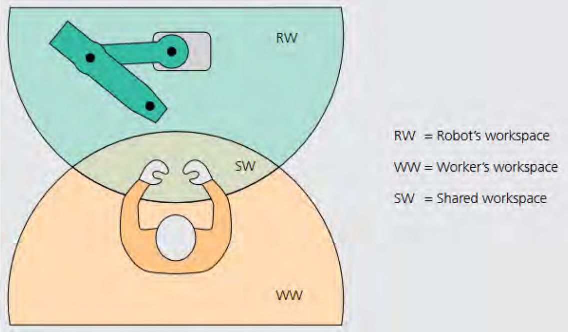


Figure 3.11: Workspaces in an HRC system (Bauer et al., 2016)

The operator and robot's workspace can overlap in an HRC system which creates a common workspace as seen in Figure 3.11. Using the amount of interaction in the common workspace between the human and robot, the level of collaboration have been defined as seen in the Figure 3.12.

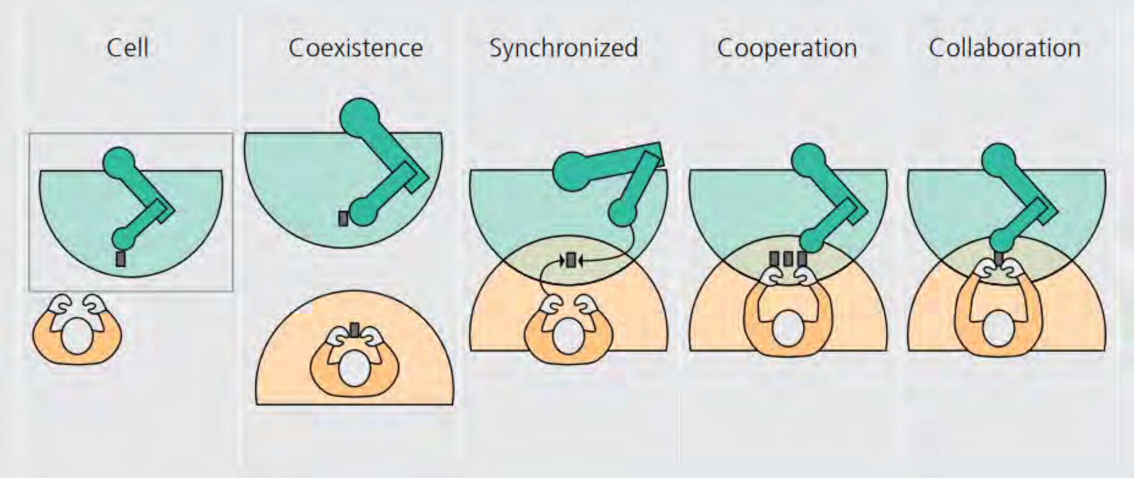


Figure 3.12: Level of Collaborations possible in an HRC system (Bauer et al., 2016)

- **Cell:** Represents the traditional scenario where the robot is bounded by a barrier separate from the operator.
- **Coexistence:** The physical barrier is not needed for the task but there is no common workspace between the operator and the robot.
- **Synchronized:** There exists a common workspace between the operator and robot, where the task is being performed but at one time, either the operator or robot can be engaged in it.
- **Cooperation:** The operator and robot use the common workspace together but are working on different tasks.
- **Collaboration:** The operator and robot work on the same task in the common workspace simultaneously. (Bauer et al., 2016; Salunkhe, Stahre, et al., 2023)

These systems can use collaborative robots (cobots) instead of traditional robots. Cobots are designed to operate, interact and cooperate alongside human operators. They are not restricted by workspace boundaries that limit industrial robots. The differences between a cobot from conventional industrial robots are enhanced safety features, proximity functions, relatively easy programming and easy deployment in factory settings (Weiss et al., 2021).

A collaboration-level assembly process includes combining the adaptability of a human operator with the precision and load-handling capabilities of a robot. This approach also minimises the repetitive tasks that cause fatigue in humans which could result in reduced production costs. The study Navas-Reascos et al., 2022 has also suggested that a human-robot assembly process is more cost effective than a complete manual or a complete automated solution.

3.5 Literature Study

One of the most unergonomic tasks in the assembly of wire harnesses is the mating of the cable connectors. This task is not only time-consuming and requires precision but also is repetitive and monotonous work. This can lead to occupational health issues like carpal tunnel syndrome and tendinitis can result from repetitive movements and exertion in wire harness assembly workers (Realyvásquez-Vargas et al., 2019). This literature study aims to explore the current state of research on the assembly of WHA focusing on automation. Aspects, methods and tools for Human-Robot collaboration that are relevant for automation in wire harness assembly have also been explored.

This section is divided into two parts, the first part focuses on the studies done on the WHA along with the current automation techniques used, the second part focuses on the studies on the Human-Robot collaboration in WHA.

Even though most research papers studied focus on the topic of automation in the manufacturing of the wire harnesses and not on the specific assembly of them on the final products, the processes involved in the final assembly step are similar and these studies are hence relevant to the thesis.

3.5.1 Automation in Wire Harness Assembly

In the study, Salunkhe, Quadrini, et al., 2023, the authors conduct a comprehensive examination of existing relevant approaches and techniques to facilitate efficient and human-centred automation WHA in the automotive industry. They present hurdles to the lack of automation in the final assembly of the WHA. According to Salunkhe, Quadrini, et al., 2023, the current assembly process of the WHA in the vehicle for an automotive manufacturer is manual today making it demanding and highly unergonomic and leading to musculoskeletal disorders (MSD). The relevant studies from the perspective of the mating of connectors identified were Jiang et al., 2015; Sun et al., 2010; Trommnau et al., 2019.

Sun et al., 2010 uses a strategic approach employing the "peg-in-hole" concept that has been proposed to address challenges in the fault-tolerant assembly of electric connectors. By focusing on error recovery strategies, this method aims to mitigate common assembly errors. Although it is a study from 2010, the method used can be easily implemented using a modern collaborative robot using their inbuilt force-torque sensors and an external camera.

Jiang et al., 2015 introduces a new method of for efficient mating of connectors. This method is distinguished by utilising wire tracing techniques, inspired by human behaviours in handling similar tasks, to recognise wire harness configurations without relying on complex sensor systems. The implementation uses a three-arm robotic setup equipped with specialised grippers and force control strategies to accurately locate and engage wire harness connectors, even within complex and branched wire configurations. Though the setup used in the study is expensive and difficult to recreate without the three-arm robot, the method used for tracing is novel and solves one of the biggest issues of handling WHA, getting to the connector without the interference of the cable. If implemented, this method can provide significant improvements to the system being developed.

Trommnau et al., 2019 suggests two ways to implement automation in WHA, to either develop more solutions for the existing subprocesses of the assembly or a completely novel way of production of the wire harness.

Yumbla et al., 2021 used a vibrating plate to get the accurate pose of the connector with the cable. The plate was held on the cable directly and after sending vibration to it, the connector at the end of the cable was aligned in position and ready for mating.

3.5.2 Human-Robot Collaboration in Wire Harness Assembly

In Navas-Reascos et al., 2022, the authors conducted a literature review on the current state of the wire harness assembly supported by collaborative robots. According to research, cobots can significantly improve ergonomics by taking on repetitive and physically demanding tasks. The main barriers identified for implementing automated solutions in wire harness assembly are the flexibility of the cables, a large variety in the parts, complexity and the high number of parts. The assembly tasks that were automated at the time of the release of the study were cable routing and electrical connector mating. The study also concluded that the research papers found for the study on human-robot collaboration in wire harness assembly are relatively new and further research is needed to support the wire harness manufacturing industry.

It was also found by Capitanelli et al., 2018 that cobots have difficulty manipulating articulated objects due to several factors including the complexity of the flexible objects' geometrical characteristics and difficulty involved in sequencing and execution of the actions. These difficulties are only compounded further by the need to adapt to unpredictable human interventions.

Gualtieri et al., 2020 did a conversion of a manual wire harness assembly workstation into a collaborative one which was found to be much safer and more ergonomic. They achieved their goal of reducing awkward postures for assembly workers by giving the task of taping collocation to the cobot.

Navas-Reascos et al., 2023 compared two workstations doing the cable tie collocation task on the wire harness assembly process, one with the manual assembly and the other with a collaborative robot, using cost-benefit analysis. The key variables identified were worker salaries, cycle times and investment costs. The key conclusion from the study was that the breakeven point, i.e. the point where the production cost of the collaborative station is equal to the production cost of the manual station in terms of the number of products produced. Another important factor identified was the country where the wire harness manufacturing enterprise is located. The third critical factor was the duration of the tasks executed by the cobot. Though the CBA could not objectively quantify the ergonomic conditions, the authors have asked for further research to consider them in the quantification.

Heisler et al., 2020 looked into how the wire harness assembly process can be optimised using human robot collaboration. The study addresses the complexity and inefficiencies in manual assembly, which, according to the authors, is due to the flexible nature of the materials and the amount of variations involved. The study found that tasks with higher ergonomic risks are better performed by robots and tasks requiring dexterity are better to be performed by humans. One of the key results is that for pre-assembly tasks involving insertion, a robot is better suited. Some identified challenges were that workstations would need to be modified for effective material provisions for the robot, and training would be needed for operators to work with the robots.

4

Results

In this chapter, we share the findings from our study, showing how our methods helped solve the main problems. We explain what these results mean for making connector mating better in wire harness assembly.

4.1 Expert Insights and Requirement Gathering

This section focuses on to gather knowledge about the cables, connectors, automatic assembly and challenges with manual assembly of wire harnesses through interviews with experts in the area.

4.1.1 Expert Interviews

During the planning phase of the project, interviews were conducted with engineers from industry, academics, operators and stakeholders. A list with content of conducted interviews is provided in sections 4.1.1.1 & 4.1.1.2.

4.1.1.1 External Interviews

- **Interview with engineer at Volkswagen**
  During the interview, the challenges associated with automating connector insertion were discussed. Volkswagen, like other companies, encountered difficulties when attempting to automate the assembly process using robots. Connectors, due to their intricate shapes, pose challenges in terms of grasping and securing. Altering the design of connectors and wire harnesses can result in elevated costs. Despite this, wire harnesses (WH) remain one of the most expensive components in a vehicle. Introducing a novel design could enhance the feasibility of automation in the future. Additionally, wire harnesses exhibit shape complexity, owing to their high degree of freedom. While multiple companies have demonstrated fully automatic processes, these cases tend to oversimplify the challenges posed by crowded wire harnesses in larger systems.

- **Interview with engineer at Atlas Copco**
  An interview was conducted with an engineer at Atlas Copco, exploring challenges associated with the automation of Wire Harness Assembly (WHA). The company has encountered difficulties in identifying and separating cables from one another. They are investigating the feasibility of automating the assembly process through alterations in connector and wire harness design. This is done

through implementation of design for automatic assembly. Additionally, the company is exploring the utilization of technologies such as sensors, software, and vision systems to aid in WHA. However, modifying connector designs may incur high costs; nonetheless, reducing process variation is imperative for successful automation implementation.

- **Interview with Postdoc at Chalmers**
  The process challenges associated with Wire Harness Assembly (WHA) were discussed with a Postdoctoral researcher at Chalmers University of Technology, who specializes in Human-Robot Collaboration (HRC). According to the interviewee's experiences, one of the primary challenges in WHA automation lies in the alignment of the robot. Given the various levels of HRC, it is recommended that this particular case be deliberated with line managers during the implementation phase. In WHA tasks, robots are predominantly utilized for pushing connectors. Due to time constraints inherent in the thesis, it is advisable to concentrate efforts on alignment and pushing tasks, while also elucidating the role of humans in the process.

4.1.1.2 Internal Interviews (Scania)

- **Interview with Therese Björnängen, development engineer**
  According to Björnängen, the objective is to maintain consistency in connector selection due to cost-effectiveness and familiarity with their operational dynamics throughout assembly, production, and maintenance processes. While newer modules necessitate updated connectors, older modules retain compatibility with legacy connectors. Connector procurement involves sourcing from various suppliers to balance cost considerations and operational requirements. The design of Engine Control Unit (ECU) connectors is undertaken in-house. Each pin within the connector exerts a contact force of 10 Newtons. Modifying the pin material aims to facilitate seamless joining between the ECU and connector. The elevated joining force of connectors is attributed to substantial cabin vibrations, necessitating durability for a 15-year service life. Increasing the number of pins would augment joining force, hence, one potential solution involves reducing pin thickness while concurrently augmenting their quantity. Enhancing tolerances and incorporating specialised tools would further enhance ergonomic considerations.

- **Interview with operator at Oskarshamn**
  The challenges of ergonomic conditions in the assembly process were discussed with an operator. This conversation took place during execution of assembly process on the assembly line, providing firsthand observation of the process and insights into associated difficulties. According to the operator, the high joining force required during assembly significantly impacts the fingers and wrists, causing strain on the body. Although a tool is available to help leverage force and minimize strain, there is a risk of damaging the connector when using this tool. Additionally, operators tend to develop increased muscular power over time, which may make joining easier through manual force alone, although this

still does not meet ergonomic standards. However, due to stringent tolerances, the operator must first align the connector manually before using the tool, thereby increasing the complexity and steps involved in the assembly process.

4.1.2 Requirement Specification

By examination of the problem through research papers in the starting phase of this project, interviews with several experts, examination of the ergonomic assessment made at station A & B, where the mating process is ergonomically demanding on the instrument panel, and the initiative from EWASS to implement automation on assembly of cables to support human operators a requirement specification was compiled. This is to create clarity around the project's objectives, and goals and also as a communication tool between different stakeholders.

These requirements have been placed in the rows of the compiled requirements specification, see Table A.1. The columns have been divided into several different categories. The first column describes what type of criteria each requirement has. The second column specifies whether the requirement is a requirement (R) or a desire (D). The third column specifies a target value where each requirement or desire is fulfilled if this target value is achieved. The fourth column specifies the importance of a desire 1-5, where 1 is the least important and 5 is the most important. The fifth column specifies how a requirement or desire is verified. The last column specifies the origin of the requirement and desire. The internal requirements and desires are set by the thesis team, see Table A.1.

The compiled requirements specification consists of four requirement categories. These categories are ranked from one to four on the rows. The first category is Improved Ergonomics for Operator which is the main goal of this thesis project. The sub-requirements in this category are extracted from the SES assessment made at station A line IB2. These criteria are used by Scania to determine whether the ergonomic standards during the performance of assembly tasks are met. The criteria that have been used in this requirement specification concern the installation of the connectors grey and blue into the ECU CUV3, see Figure 4.6. Requirement 1.1 refers to the size of the surface area of the connector that will be subjected to pressure with a finger during pairing. The defined target value is an area size larger than the connector's area for pressing. In other words, this means the target value area is larger than the existing connector area, which ultimately leads to an improved ergonomic condition. If the joining is performed by a robot, this requirement will thus be fulfilled since the involvement of a human being is excluded. Requirement 1.2 is of the same nature as requirement 1.1 except that requirement 1.2 refers to the area of the palm thus a larger target value.

Requirements 1.3 and 1.5 refer to the amount of force that a connector will need to be exposed to for a pairing to take place. This is when the hand is in a neutral position, see Figure 3.7. As mentioned in the previous paragraph, the defined target values are intended for improved ergonomic conditions. The target values for the force amounts are smaller than the amounts that the connectors today require for joining. Requirement 1.3 is intended for one finger and requirement 1.5 refers to the use of all fingers therefore higher target value. Desire 1.4 and 1.6 have smaller values than the same family of requirements. Requirements 1.7 and 1.9 and desires 1.8 and 1.10 follow the same principles as requirements 1.3 and 1.5 and desires 1.4 and 1.6. The difference that stands out in these requirements and desires is that they are intended for when the wrist is in the extreme position, see Figure 3.7.

Requirement family two concerns technical requirements on the condition that automation is to be implemented in the installation of wiring harnesses. Requirement 2.1 is set by the EWASS project where automation is to be implemented to strengthen the work of operators in the assembly of wiring harnesses. Therefore, the goal is that at least one of the steps in assembling the connectors in the ECU must be performed by a robot. Requirement 2.2 refers to the quality work of the robot and safety during the execution of the assembly process. Requirement 2.3 is set internally which prohibits the team from using any conventional solution that is already used to improve the ergonomic condition of the operator. Requirement family three refers to how efficient the entire process should be, regardless of whether it would involve human-robot collaboration or take place completely automatically. Here, a desire was presented where the target value is the time it currently takes to assemble the connectors in the ECU CUV3 manually.

Requirement category four defines criteria to be taken into account if the final concepts will be implemented in the production line. The integration criteria here are set as a desire since the project's intention is not implementation but exploration of several final concepts.

4.2 Concept Generation

This section focuses on generation of concepts through a Function-means Tree and a Morphological Matrix. Final generated concepts are presented in a Concept Catalogue.

4.2.1 Function-means Tree

The Functions-means tree developed serves the primary goal of systematically outlining the process steps involved in cable assembly, breaking down the main process into its constituent sub-functions. This decomposition aids in a detailed understanding of the operational framework and facilitates the generation of concepts for each sub-function.

The main function of the Functions Means Tree is Mate Connectors and ECU, with the means represented by the Collaborative Robot System. Following this hierarchical structure, the means is further decomposed into six sub-functions: Identify Connector, Grasp Connector, Manipulate Connector, Align Connector, Join Connector, and Confirm Joining, see Figure 4.1. These components were identified based on observations, interviews, and practical engagement with the cable assembly process conducted within the factory by human operator and team members in the Smart Factory Lab.

The Functions Means Tree presents a clear visual representation, with main functions located in trapezoid shapes and means in rectangles. The process flow initiates from the left with the Identify Connector and progresses sequentially through each sub-function until reaching Confirm Joining on the right. Every functionality of the process is presented by a verb+noun.

This methodology simplifies the complex process into manageable steps, thereby facilitating the generation of various concepts for each sub-function. The iterative combination of these sub-solutions offers a diverse array of potential total solutions, which are further explored through the Morphological Matrix.

Although challenges were encountered during the compilation of the Functions Means Tree, particularly in precisely identifying process functionalities, these hurdles were addressed through extensive discussions with supervisors, team deliberations, and hands-on observations.

The validation of the Functions Means Tree lies in its practical application during concept generation and testing. By fulfilling the requirements of the process and aiding in the development and assessment of concepts, the Functions Means Tree demonstrates its efficacy as a systematic tool for process analysis and innovation.

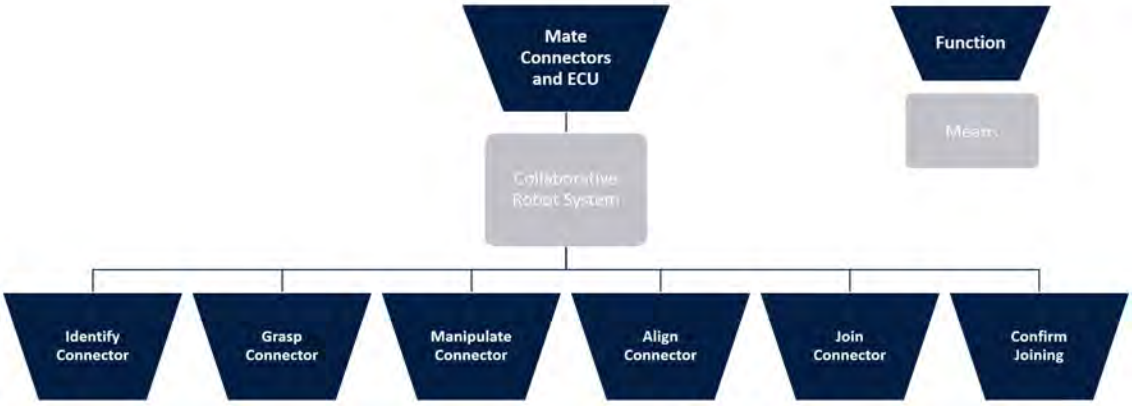
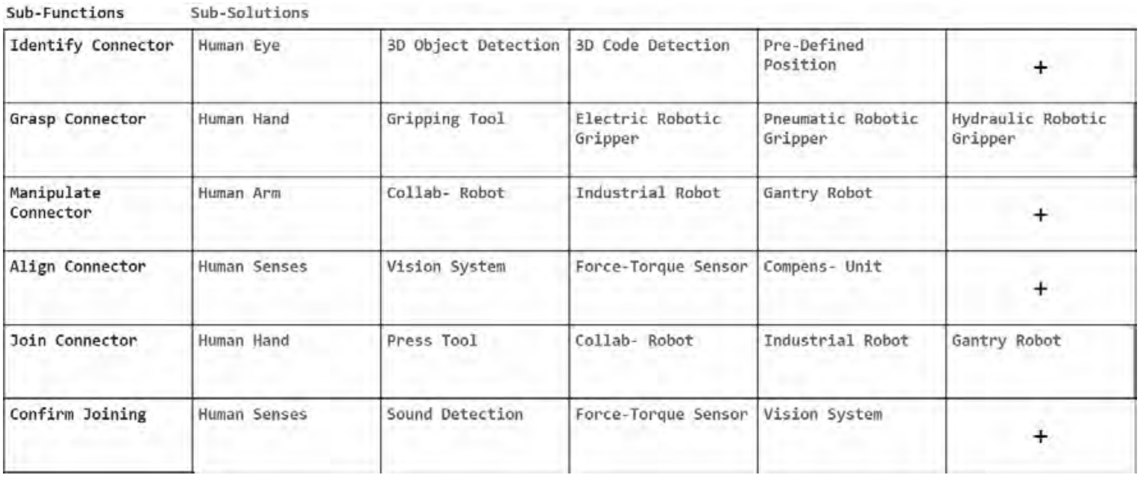


Figure 4.1: Function-means Tree

4.2.2 Morphological Matrix

Based on the compiled Functions-means Tree, a morphological matrix was compiled to generate several concepts for each Sub-Function in the Functions-means Tree. The aim was to produce as many concepts as possible to explore various potential total solutions. This session involved brainstorming within the team, discussions with the responsible supervisor at Scania, drawing inspiration from interviews, and studying existing technologies in the market. During the concept generation phase, resource limitations were initially disregarded to maximize the number of concepts, see Table 4.1. To compile a morphological matrix and generate, disable concepts and define incompatibilities the tool Morpheus(“Morpheus”, 2024) was used.

Table 4.1: Morphological Matrix



Sub-Functions	Sub-Solutions				
Identify Connector	Human Eye	3D Object Detection	3D Code Detection	Pre-Defined Position	+
Grasp Connector	Human Hand	Gripping Tool	Electric Robotic Gripper	Pneumatic Robotic Gripper	Hydraulic Robotic Gripper
Manipulate Connector	Human Arm	Collab- Robot	Industrial Robot	Gantry Robot	+
Align Connector	Human Senses	Vision System	Force-Torque Sensor	Compens- Unit	+
Join Connector	Human Hand	Press Tool	Collab- Robot	Industrial Robot	Gantry Robot
Confirm Joining	Human Senses	Sound Detection	Force-Torque Sensor	Vision System	+

For the sub-function "Identify Connector", four concepts were developed. Currently, identification of the connector is performed by human operators using their vision. An alternative approach involves utilizing 3D Object Detection technology. This technology, a subset of computer vision, detects objects based on their shape, location, and orientation(Code, 2024). Another concept involves 3D Code Detection, where a laser scans a barcode attached to the object, with the reflection of black and white bars converted into a digital signal(Wave, 2024). Additionally, a concept known as "Pre-Defined Position" was generated. This concept involves predefining the coordinates of the object in space, enabling users to know where to locate and grasp the object.

For the sub-function "Grasp Connector" five concepts were developed. To first concept that was generated in this phase was that the object can be grasped by a Human Hand. This process is already done by the operator. The next concept that was developed was a Gripping Tool. A pliers can be used as a gripping tool to grab the object in this case. The third, fourth and fifth concepts were different types of grippers that can be attached to articulated robots(robots with rotary joints)(Right, 2024). Hydraulic grippers use pressurized fluids to supply power and are used for heavy cases $>50kg$. Pneumatic grippers use compressed air to apply gripping force on an object. They offer high forces within a compact, lightweight, and cost-effective design(Robots, 2021). Electric grippers use electric motors to operate. They are mostly used for Cobot cases and pick & place tasks and adjustable for varying forces and speed(Robots, 2020).

For the sub-function "Manipulate Connector" four concepts were developed. Manipulation of the connector can be done by a human hand manually. This task is already done by the operator at the Oskarshamn factory. Manipulation of the connector can also be done by a robot arm using Collaborative robots, Industrial robots or Gantry robots. Collaborative robots are usually light-weight robotic arms and have the characteristics of sharing tasks and work areas with humans. They can be used for many variety of applications(Robots, 2024). Industrial robots, in this case, refer to size robot arms that are used for big and heavy objects for example windshields. These robots are programmed for repetitive tasks with high speed and precision(Becher, 2024). Gantry robots are robot arms moving on rail systems in xyz-directions. Gantry robots are mostly used for heavy payloads and in large areas(Rao, 2023).

For the sub-function "Align Connector" four concepts were developed. For alignment of the connector in the socket, Human Senses can used. A human can manipulate the connector and confirm the alignment using his or her senses. This process is already done by the human operator at Oskarshamn. On the other hand, a vision system can be used to know if the object is aligned well in position. Here the the goal is to use a computer vision(IBM, 2024) to detect the object and distances needed for alignment. Another concept that was presented for aligning the connector was using a Force-Torque Sensor(Lika, 2023). A force-torque sensor is a device that is attached to or integrated into the robot arm. It measures the force and torque needed to guide the robot to its right path. Lastly, the Compensation Unit was also presented to use for the alignment of the robot arm to the socket. Compensation unit(SCHUNK, 2024b) is a device which is attached to the robot arm and can be used to compensate the offset during aligning.

The first two concepts for the sub-function "Join Connector" that was presented were using a human hand or a pressing tool. These two concepts are already used in the assembly line by a human. The pressing tool that is used is a pliers which put less pressure on the operator's hand and wrist. The other three concepts that were presented were collaborative robot, industrial robot and gantry robot. These three concepts were also presented for the sub-function "Manipulate Connector" and explained there under that paragraph.

For the sub-function "Confirm Joining" four concepts were generated. Firstly, human senses was presented that can be used confirm the joining of connector and the ECU. On the other hand force torque sensor and vision system can be used for joining confirmation. There concepts are elaborated on the for aligning connector sub-function. Confirm joining can also be done by sound detection. This could be used by detecting a clicking sound waves through a sensor as a confirmation. The involved connectors in this project have extra edge as a locking system which gives a clicking sound after joining.

4.2.3 Concept Catalogue

The principle of the morphological matrix is to combine different sub-solutions for each sub-function with the sub-solutions for other sub-functions to generate complete solutions. Since the process was divided into six sub-functions and four sub-functions have 4 concepts and 2 sub-functions have 5 concepts, this gives rise to a total of 4*5*4*4*5*4 = 6400 total solutions. Theoretically, this means that the problem could be solved with every single one of these 6400 solutions, however there are exceptions.

First of all, after discussions in the team and taking into account the plausibility level and resources, some sub-solutions were marked from the morphological matrix. For the sub-function "Identify Connector" 3D Code Detection was disabled. This is because access to equipment for 3D code detection does not exist and 3D Object Detection provides great flexibility when it comes to variation in picking positions.

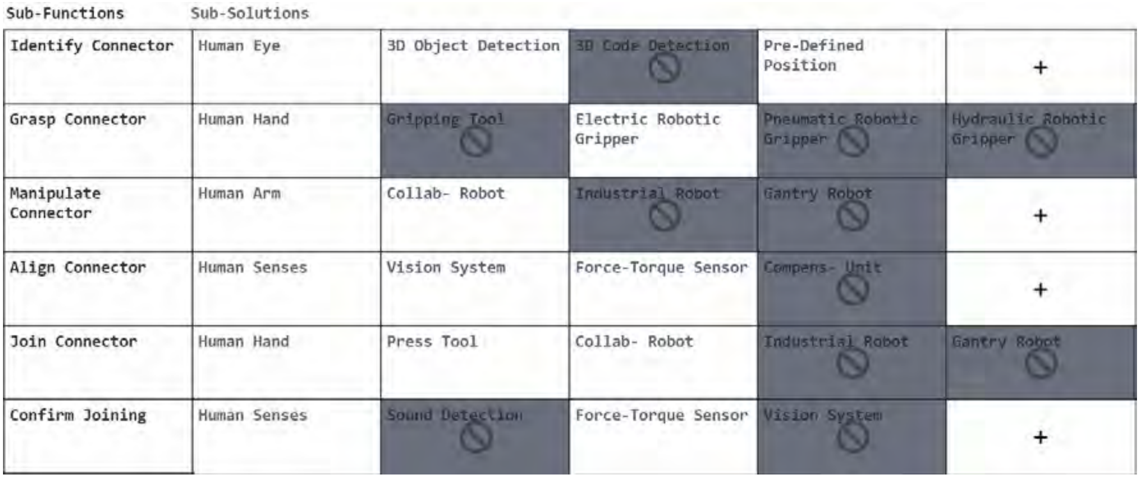
For the sub-function "Grasp Connector" three concepts were disabled. The Gripping Tool would not be used in this project because a connector can be picked by a human hand to begin with at the same time a robotic arm will be mainly used during the course of the project which will involve a gripper and therefore a Gripping Tool will lose its value. And since different gripper systems have high purchase prices, it was decided, after discussions with representatives from SCHUNK(“Company SCHUNK”, n.d.), to acquire an Electric Robotic Gripper. Therefore, the Pneumatic and Hydraulic Robotic Gripper were disabled. More explanation about these concepts can be found under subsection 4.2.2.

For the sub-function "Manipulate Connector", Industrial Robot was disabled because industrial robots are usually used for heavier tasks and usually do not share the work with a human. Gantry Robot was also disabled due to not having access to such a robot in the lab and the cost of implementing one for the execution of a thesis project for six months. Since the team had access to the UR16e, a collaborative robot which has a shorter arm and can be easily programmed for smaller applications, this robot was chosen as the main tool to implement automation.

For the "Align Connector" sub-function, the Compensation Unit concept was disabled. This is because adjustment of the connector in the socket is possible with the Vision System and Force-Torque Sensor and the team had access to these at the Smart Factory Lab. The inclusion of a compensation unit would not make a noticeable difference to the result, given the high price one would have to pay.

For the "Join Connector" sub-function, the Industrial Robot and Gantry Robot were disabled just as it was for the "Manipulate Connector" sub-function. The reasoning for removal was explained under that paragraph. For the sub-function "Confirm Joining" Sound Detection was disabled this concept would under-perform in noisy environments such as production environments. Vision System was also disabled as this concept would confirm the insertion of the plug into the socket only by distance measurement. This would not lend credibility if the connector has joined with the target socket. For achieving a better overview of which concepts were disabled see Table 4.2

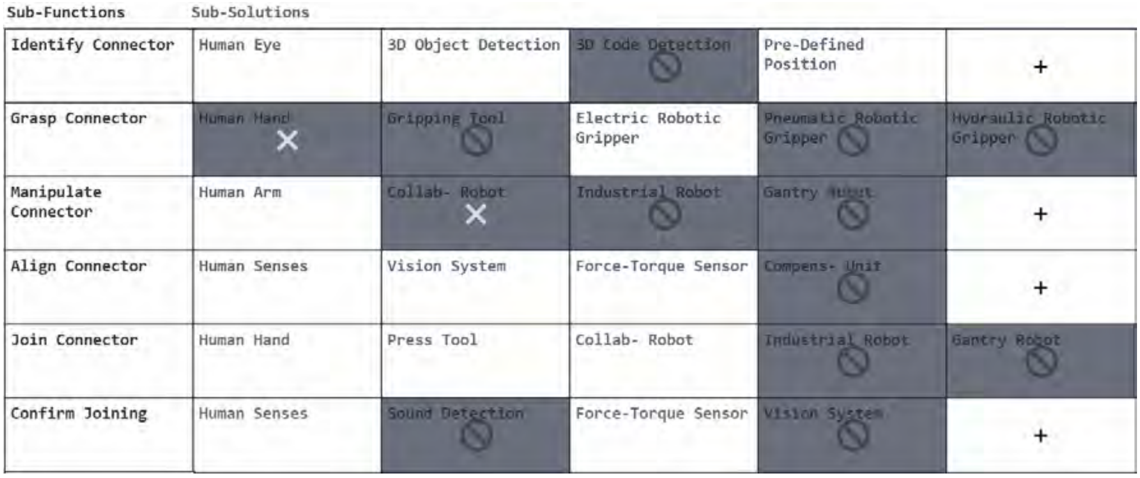
Table 4.2: Morphological Matrix, Disabled Concepts with Circle-Backslash Sign



Sub-Functions	Sub-Solutions				
Identify Connector	Human Eye	3D Object Detection	3D Code Detection ⊘	Pre-Defined Position	+
Grasp Connector	Human Hand	Gripping Tool ⊘	Electric Robotic Gripper	Pneumatic Robotic Gripper ⊘	Hydraulic Robotic Gripper ⊘
Manipulate Connector	Human Arm	Collab- Robot	Industrial Robot ⊘	Gantry Robot ⊘	+
Align Connector	Human Senses	Vision System	Force-Torque Sensor	Compens- Unit ⊘	+
Join Connector	Human Hand	Press Tool	Collab- Robot	Industrial Robot ⊘	Gantry Robot ⊘
Confirm Joining	Human Senses	Sound Detection ⊘	Force-Torque Sensor	Vision System ⊘	+

Furthermore, it was realized that some concepts are incompatible with each other. Thus it was decided to define incompatibilities between these remaining concepts that could not be combined. The first incompatibility that was defined was that the Human Hand (Grasp Connector) does not go together with the Collab-Robot (Manipulate Connector) for the obvious reason that if the connector is grasped by a human hand, the manipulation must also be performed by a human, see Table 4.3.

Table 4.3: Morphological Matrix, Defined Incompatibility with Cross Sign

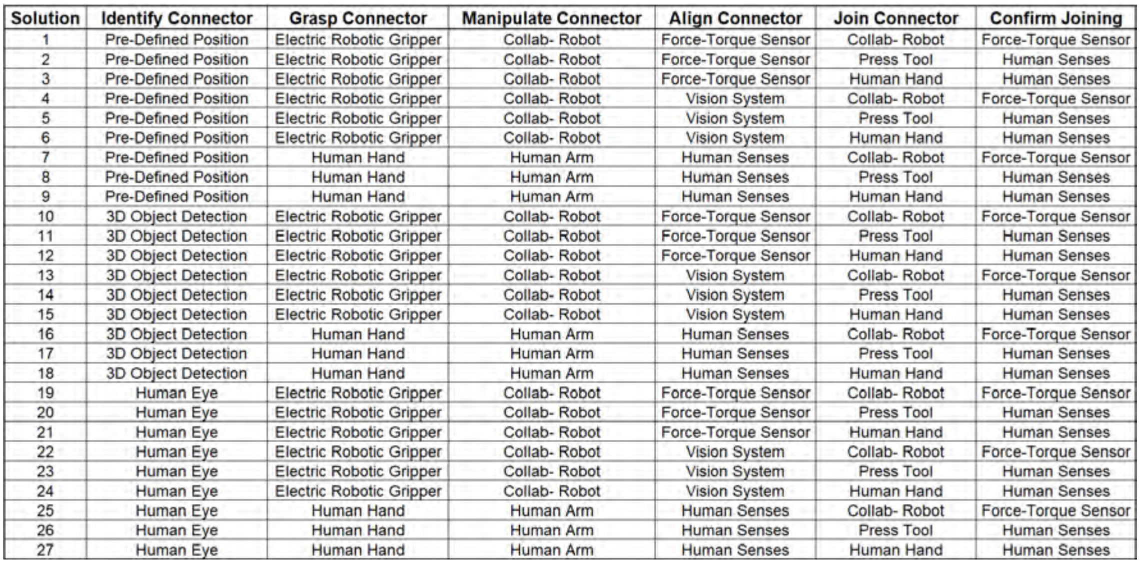


Sub-Functions	Sub-Solutions				
Identify Connector	Human Eye	3D Object Detection	3D Code Detection ⊘	Pre-Defined Position	+
Grasp Connector	Human Hand ✕	Gripping Tool ⊘	Electric Robotic Gripper	Pneumatic Robotic Gripper ⊘	Hydraulic Robotic Gripper ⊘
Manipulate Connector	Human Arm	Collab- Robot ✕	Industrial Robot ⊘	Gantry Robot ⊘	+
Align Connector	Human Senses	Vision System	Force-Torque Sensor	Compens- Unit ⊘	+
Join Connector	Human Hand	Press Tool	Collab- Robot	Industrial Robot ⊘	Gantry Robot ⊘
Confirm Joining	Human Senses	Sound Detection ⊘	Force-Torque Sensor	Vision System ⊘	+

The same logic was applied to Electric Robotic Gripper (Grasp Connector) which does not go together with Human Arm(Manipulate Connector) and Human senses(Align Connector). Another was Human Arm(Manipulate Connector) with Vision System and Force-Torque Sensor(Align Connector) for the obvious reason that the human arm cannot be combined with a force-torque sensor that is only mounted on a robot arm. The same was true for the Human Hand and Press Tool(Join Connector) which could not be combined with the Force-Torque Sensor(Confirm Joining). There was also an incompatibility between Collab-Robot(Join Connector) and Human Senses(Confirm Joining). Since joining is done by a robot, the confirmation of the pairing must therefore be performed by a robot, for example a force-torque sensor that is mounted on the robot arm and signals immediately to the robot when the connector is inserted into the socket.

After disabling and defining the incompatibility of certain concepts the total output of the compiled morphological matrix was 27 complete solutions, see Table 4.4.

Table 4.4: Concept Catalogue



Solution	Identify Connector	Grasp Connector	Manipulate Connector	Align Connector	Join Connector	Confirm Joining
1	Pre-Defined Position	Electric Robotic Gripper	Collab- Robot	Force-Torque Sensor	Collab- Robot	Force-Torque Sensor
2	Pre-Defined Position	Electric Robotic Gripper	Collab- Robot	Force-Torque Sensor	Press Tool	Human Senses
3	Pre-Defined Position	Electric Robotic Gripper	Collab- Robot	Force-Torque Sensor	Human Hand	Human Senses
4	Pre-Defined Position	Electric Robotic Gripper	Collab- Robot	Vision System	Collab- Robot	Force-Torque Sensor
5	Pre-Defined Position	Electric Robotic Gripper	Collab- Robot	Vision System	Press Tool	Human Senses
6	Pre-Defined Position	Electric Robotic Gripper	Collab- Robot	Vision System	Human Hand	Human Senses
7	Pre-Defined Position	Human Hand	Human Arm	Human Senses	Collab- Robot	Force-Torque Sensor
8	Pre-Defined Position	Human Hand	Human Arm	Human Senses	Press Tool	Human Senses
9	Pre-Defined Position	Human Hand	Human Arm	Human Senses	Human Hand	Human Senses
10	3D Object Detection	Electric Robotic Gripper	Collab- Robot	Force-Torque Sensor	Collab- Robot	Force-Torque Sensor
11	3D Object Detection	Electric Robotic Gripper	Collab- Robot	Force-Torque Sensor	Press Tool	Human Senses
12	3D Object Detection	Electric Robotic Gripper	Collab- Robot	Force-Torque Sensor	Human Hand	Human Senses
13	3D Object Detection	Electric Robotic Gripper	Collab- Robot	Vision System	Collab- Robot	Force-Torque Sensor
14	3D Object Detection	Electric Robotic Gripper	Collab- Robot	Vision System	Press Tool	Human Senses
15	3D Object Detection	Electric Robotic Gripper	Collab- Robot	Vision System	Human Hand	Human Senses
16	3D Object Detection	Human Hand	Human Arm	Human Senses	Collab- Robot	Force-Torque Sensor
17	3D Object Detection	Human Hand	Human Arm	Human Senses	Press Tool	Human Senses
18	3D Object Detection	Human Hand	Human Arm	Human Senses	Human Hand	Human Senses
19	Human Eye	Electric Robotic Gripper	Collab- Robot	Force-Torque Sensor	Collab- Robot	Force-Torque Sensor
20	Human Eye	Electric Robotic Gripper	Collab- Robot	Force-Torque Sensor	Press Tool	Human Senses
21	Human Eye	Electric Robotic Gripper	Collab- Robot	Force-Torque Sensor	Human Hand	Human Senses
22	Human Eye	Electric Robotic Gripper	Collab- Robot	Vision System	Collab- Robot	Force-Torque Sensor
23	Human Eye	Electric Robotic Gripper	Collab- Robot	Vision System	Press Tool	Human Senses
24	Human Eye	Electric Robotic Gripper	Collab- Robot	Vision System	Human Hand	Human Senses
25	Human Eye	Human Hand	Human Arm	Human Senses	Collab- Robot	Force-Torque Sensor
26	Human Eye	Human Hand	Human Arm	Human Senses	Press Tool	Human Senses
27	Human Eye	Human Hand	Human Arm	Human Senses	Human Hand	Human Senses

4.3 Concept Screening

This section focuses on screening of concepts through a Elimination Matrix and a Pugh Matrix. Concepts which do not fulfil the requirements will be removed during the screening in Elimination Matrix. Remaining Concepts from the Elimination Matrix will then be compared against each other based on criteria derived from the requirement list.

4.3.1 Elimination Matrix

As the first part of Concept Screening an Elimination Matrix was compiled, see Table A.2. The purpose of the elimination matrix was to filter out the concepts that do not meet the requirements, not the wishes, set in the requirements specification, see Table A.1. The elimination matrix that was compiled contains four main columns. Under the first column, the concept numbers are listed in the same order as the concept catalogue, see Table 4.4. Under the second column called criteria are the requirements that were set during the requirements collection phase. These requirements are marked with numbers that correspond to the same numbers in the requirements specification. Under each requirement, each concept was marked with "+" if the requirement was met and "-" for the opposite. The third column clarifies why a concept was screened out with a comment. The last column shows the decision made whether concepts should be eliminated or kept with "-" and "+". In the Elimination Matrix, concepts that did not meet at least one requirement were screened out.

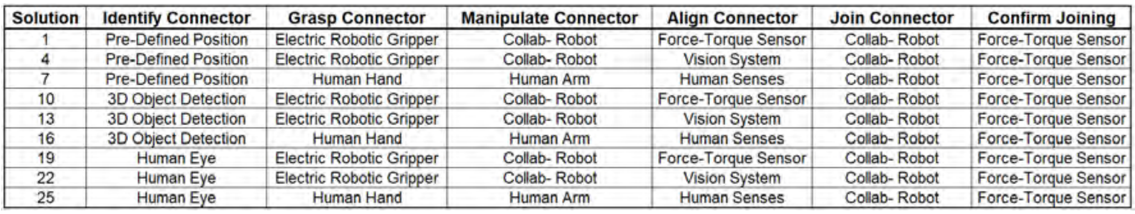
Concepts 2, 5, 8, 11, 14, 17, 20, 23 and 26 all do not fulfill requirement 2.6. This is because these concepts use a press tool to join the connector to the ECU. Since this solution is already used in production and it is not the ambition of this project to present existing solutions, the solutions were screened out.

Concepts 8, 9, 17, 18, 26 and 27 all do not meet the requirement 2.1 set by the EWASS project where automation must be implemented to facilitate the work of the operator during the assembly of cables. Thus, these concepts were screened out.

Concepts 3, 6, 9, 12, 15, 18, 21, 24 and 27 all do not meet the ergonomic requirements 1.1-1.9. This is because these concepts use a human hand to pair the connector with the ECU, which has led to an unergonomic way of working, see sub-section 3.3.3. The solutions that meet these requirements are solutions that use a robot to perform the joining, which replaces a human hand entirely.

It is worth mentioning that the Elimination session was not conducted by digital or physical tests but by reasoning, logical thinking and with the help of discussions in the team members. The remaining concepts after the screening are shown in Table 4.5.

Table 4.5: Remaining Concepts after Elimination



Solution	Identify Connector	Grasp Connector	Manipulate Connector	Align Connector	Join Connector	Confirm Joining
1	Pre-Defined Position	Electric Robotic Gripper	Collab- Robot	Force-Torque Sensor	Collab- Robot	Force-Torque Sensor
4	Pre-Defined Position	Electric Robotic Gripper	Collab- Robot	Vision System	Collab- Robot	Force-Torque Sensor
7	Pre-Defined Position	Human Hand	Human Arm	Human Senses	Collab- Robot	Force-Torque Sensor
10	3D Object Detection	Electric Robotic Gripper	Collab- Robot	Force-Torque Sensor	Collab- Robot	Force-Torque Sensor
13	3D Object Detection	Electric Robotic Gripper	Collab- Robot	Vision System	Collab- Robot	Force-Torque Sensor
16	3D Object Detection	Human Hand	Human Arm	Human Senses	Collab- Robot	Force-Torque Sensor
19	Human Eye	Electric Robotic Gripper	Collab- Robot	Force-Torque Sensor	Collab- Robot	Force-Torque Sensor
22	Human Eye	Electric Robotic Gripper	Collab- Robot	Vision System	Collab- Robot	Force-Torque Sensor
25	Human Eye	Human Hand	Human Arm	Human Senses	Collab- Robot	Force-Torque Sensor

4.3.2 Pugh Matrix

The team decided to compare and evaluate the winning concepts from the Elimination Matrix against each other with a number of criteria as a basis. As a the second part of concept screening process phase, a Pugh matrix was compiled that enabled this process. The aim of this step was to explore how well different concepts will perform against each other base on some criteria.

The complied Pugh Matrix contained eight criteria, six of which are the inspired from the requirements specification. The only new criteria that has been added is variation friendly and reliability. In these matrices, a concept was chosen as a reference, which meant that all other concepts were compared to this concept. If a concept performed better against a criterion compared to the reference concept, it was rated "+" and "-" for the opposite. If a concept weighed equally together with the reference concept against a certain criterion, the concept was rated with "0". Addition of all "+" and "-" on each concept resulted in a Net Worth value. Based on this Net Worth value, the different concepts were ranked. In theory, a concept was discarded if this received a Net Worth value less than 0. Since the project was open-ended and several concepts would be presented, it was decided that the Pugh Matrix would be used as a decision-making tool, which means that even if a concept would underperform, that concept would be taken forward if it has potential.

First of all, it was to decide which criteria are suitable to use in order to be able to compare the different concepts with each other. Although the concepts in the Pugh Matrix all meet the ergonomic requirement when it comes to pairing the connector with the ECU, it was thought that these concepts should also be compared with each other because some concepts involved a human more than the others(HRC), which in itself can expose operators to more stress during the execution of other process steps. Thus, ergonomics a general was chosen for a criterion.

Collision avoidance was one of the requirements that was met by all concepts, however, it was reasoned that should any concept use human-robot cooperation, the risk of injury to the operator increases, thus safety was chosen as a criterion.

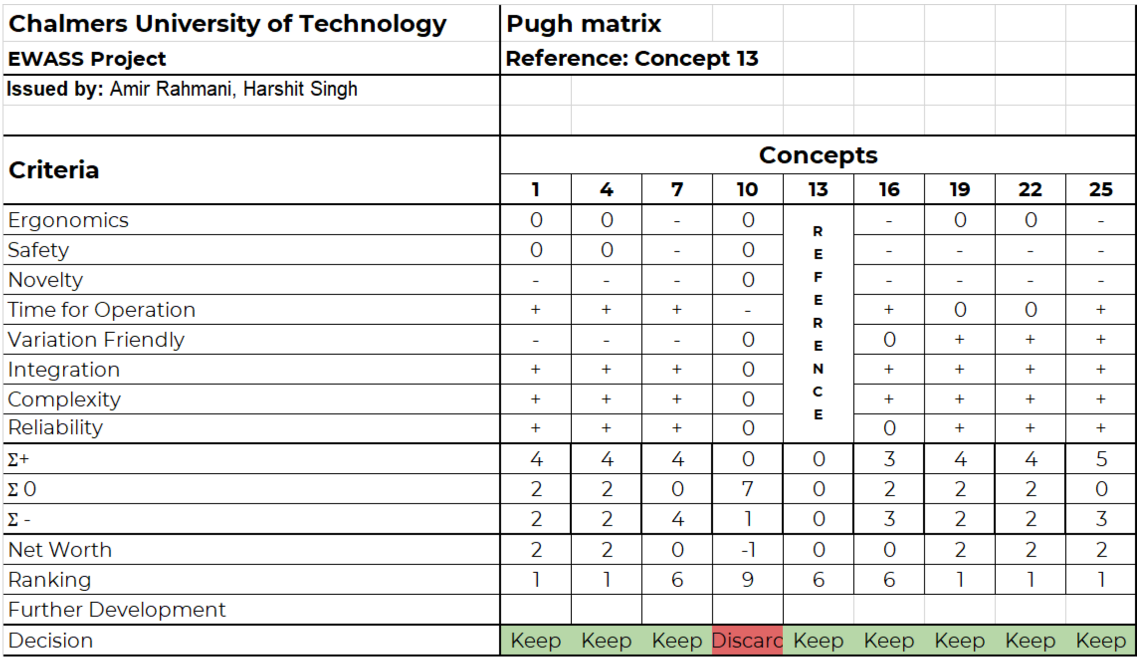
Requirement 2.3 non-conventional ergonomic enhancement methods referred to solutions used today to improve the ergonomics of the operator. Here, this requirement was used to produce two criteria. One was novelty and the other was complexity. The novelty referred to how new the concept is in comparison to existing solutions. The complexity referred to which and number of advanced tools would be needed for the concept to succeed.

Criteria time for operation and integration are already in the list of requirements as desires, however it was of high value to have these as criteria. Time for operation in the requirements list is the time it takes for an operator to complete the assembly process, however this criterion has no limit here but it measures how fast different concepts are in performing the process against each other. Integration, on the other hand, refers to the possibility of implementing the concept on the assembly line in the current situation.

Variations friendly and operational reliability are the two criteria that were inspired by the challenges that were noticed during the observation of the problem of cables and assembly. Variety-friendly refers to the randomness of the presentation of cables in the instrument panel because they are scattered all over the place where there are a large number of connectors of different models, sizes and shapes. Operational reliability refers to how often a concept succeeds in performing all assembly steps without failure.

During the first iteration of the Pugh matrix, concept 13 was chosen as a reference due to its high complexity. This concept will be used as an exploration concept since there are currently no ambitions for implementation, see Table 4.6. The result of the first iteration showed that concept 10 did not perform as well as the reference concept 13. Only differences between concept 10 and 13 were that they used different tools for aligning the connector into the ECU. Thus, it was unnecessary to retain it, hence this was discarded.

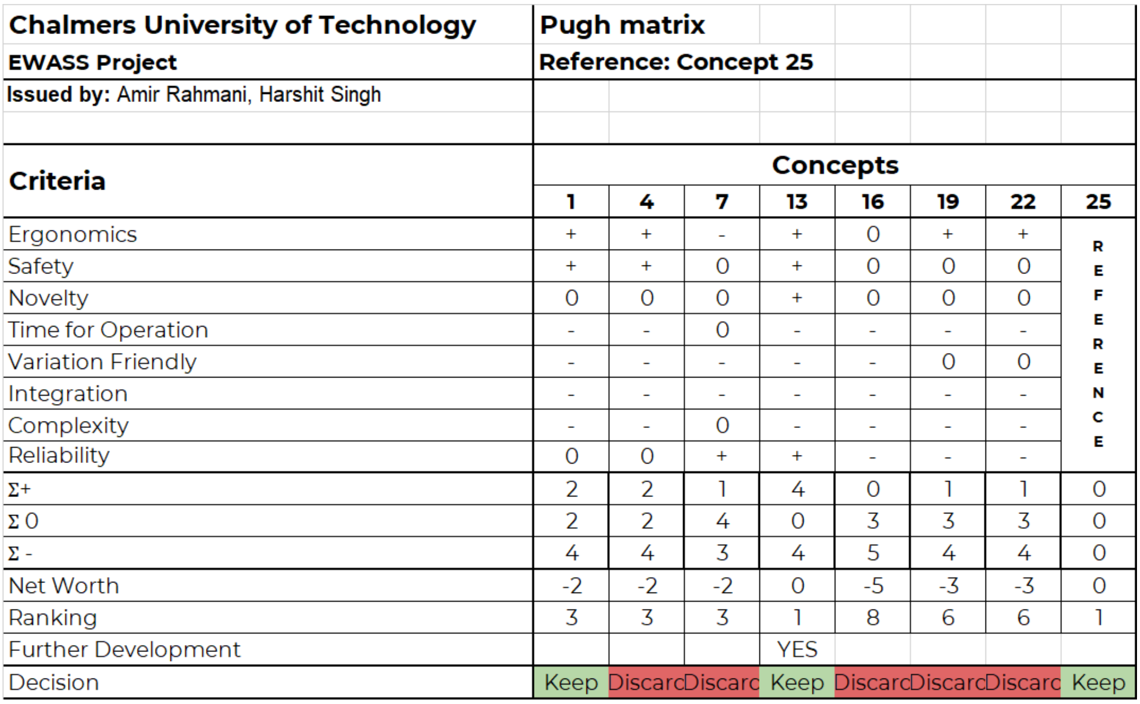
Table 4.6: Pugh Matrix, First Iteration



Chalmers University of Technology	**Pugh matrix**								
EWASS Project	**Reference: Concept 13**								
Issued by: Amir Rahmani, Harshit Singh									
Criteria	**Concepts**								
	1	**4**	**7**	**10**	**13**	**16**	**19**	**22**	**25**
Ergonomics	0	0	-	0	REFERENCE	-	0	0	-
Safety	0	0	-	0		-	-	-	-
Novelty	-	-	-	0		-	-	-	-
Time for Operation	+	+	+	-		+	0	0	+
Variation Friendly	-	-	-	0		0	+	+	+
Integration	+	+	+	0		+	+	+	+
Complexity	+	+	+	0		+	+	+	+
Reliability	+	+	+	0		0	+	+	+
Σ+	4	4	4	0	0	3	4	4	5
Σ 0	2	2	0	7	0	2	2	2	0
Σ -	2	2	4	1	0	3	2	2	3
Net Worth	2	2	0	-1	0	0	2	2	2
Ranking	1	1	6	9	6	6	1	1	1
Further Development									
Decision	Keep	Keep	Keep	Discarc	Keep	Keep	Keep	Keep	Keep

The first iteration of the Pugh matrix resulted in several winning concepts. For increased legitimacy of the screening process, it was decided that one more iteration would be carried out, see Table 4.7. In the second iteration, concept 25 was chosen as a reference because this concept involved a human in the assembly process more than all others, thus a higher degree of human-robot collaboration. It was reasoned that concept 25 has a lower degree of complexity and great opportunities for integration. This is to explore how the most automatic concepts behave in relation to a more human-involved one. The result showed the winner in this screening process was concept 13. This concept had a higher degree of complexity therefore it was decided that a further development of this concept should be carried out. Due to the open-minded nature of the project, it was decided to present one more concept in addition to the winning concepts. Concept 1 and 4 were very similar to each other with the only difference being that concept 4 would use a vision system. Since the vision system was already used in concept 13, it was not considered necessary to keep concept 4 and instead keep concept 1 for testing. Concept 7 and 16 were extremely similar to concept 25 but less efficient and reliable in execution therefore these were sacrificed. Concepts 19 and 22 were also discarded because these concepts can be divided into Concepts 1 and 25 where one is fully automated and the other with a higher degree of human-robot collaboration.

Table 4.7: Pugh Matrix, Second Iteration



Chalmers University of Technology	**Pugh matrix**							
EWASS Project	**Reference: Concept 25**							
Issued by: Amir Rahmani, Harshit Singh								
Criteria	**Concepts**							
	1	**4**	**7**	**13**	**16**	**19**	**22**	**25**
Ergonomics	+	+	-	+	0	+	+	**REFERENCE**
Safety	+	+	0	+	0	0	0	
Novelty	0	0	0	+	0	0	0	
Time for Operation	-	-	0	-	-	-	-	
Variation Friendly	-	-	-	-	-	0	0	
Integration	-	-	-	-	-	-	-	
Complexity	-	-	0	-	-	-	-	
Reliability	0	0	+	+	-	-	-	
Σ+	2	2	1	4	0	1	1	0
Σ 0	2	2	4	0	3	3	3	0
Σ -	4	4	3	4	5	4	4	0
Net Worth	-2	-2	-2	0	-5	-3	-3	0
Ranking	3	3	3	1	8	6	6	1
Further Development				YES				
Decision	🟩 Keep	🟥 Discarc	🟥 Discarc	🟩 Keep	🟥 Discarc	🟥 Discarc	🟥 Discarc	🟩 Keep

4.4 Concept Refinement

This section focuses on Preparation of the Setup, First Iterations and presentation and test results of Final Concepts derived from the second iteration of Pugh Matrix. Different finger designs are also presented which are aimed for different purposes.

4.4.1 Preparation

In order to test and validate the various presented concepts in the Pugh matrix the necessary equipment needed to be installed. To begin with, the various concepts needed to be tested on the instrument panel, therefore an area in the Smart Factory Lab was intended for the building of the entire station. The instrument panel was mounted on an orange fixture which in turn was placed on a table, see Figure 4.2.

Figure 4.2: Test Setup of Instrument Panel in the Smart Factory Lab

All the concepts presented involve a collaborative robot thus a UR 16e, which was available in the lab, was used in this project. The robot was placed on a table next to the table with the instrument panel, see Figure 4.3.

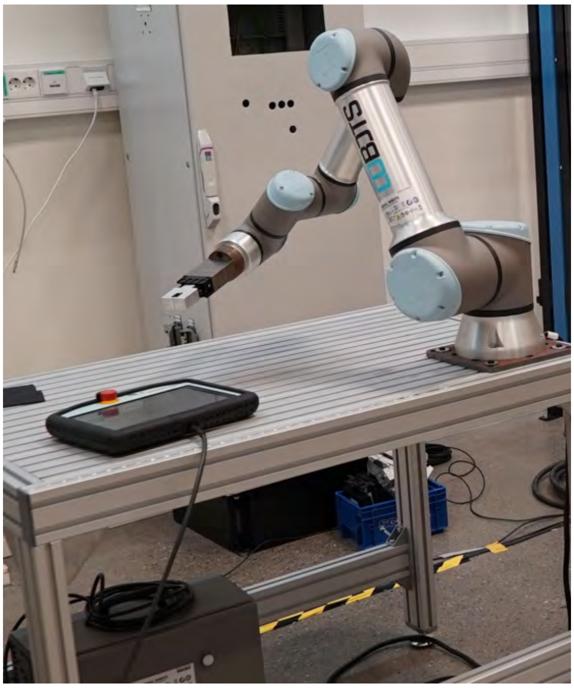
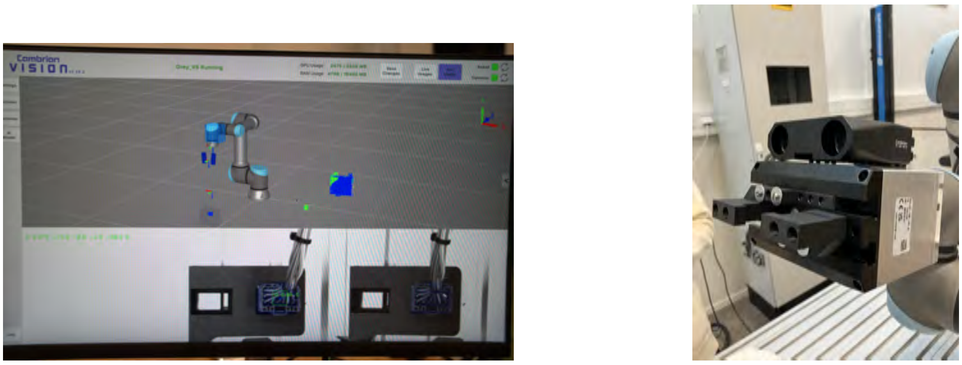


Figure 4.3: Collaborative Robot UR16e

Since concept 13 uses a vision system for aligning and 3D object detection, Cambrian's vision system was used in this project("Home - Cambrian", 2024). The system includes software and a camera that is mounted on the robot itself, see Figure 4.4. In the software, the pick points are defined on the object's CAD file in a platform called PickEditor. The model is then trained in a synthetic database as part of machine learning. It is worth noting that the training of the model was carried out by Cambrian themselves and not the thesis workers. The AI model will then be uploaded into the software connected to the camera. When the object and pick points are detected by the camera, the exact coordinates will be sent to the software, which in turn communicates with the robot and commands the robot's approach target("Product - Cambrian", 2024).



(a) Software **(b)** Camera

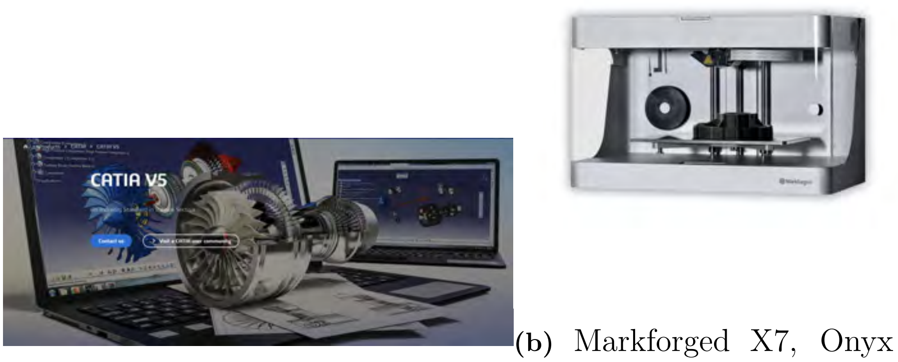
Figure 4.4: Cambrian Vision System

After discussions with SCHUNK representatives, an electrical gripper was purchased. This gripper was installed on the robot arm and used during experimentation of the different co-concepts, see Figure 4.5.

Figure 4.5: SCHUNK Electrical Gripper("SCHUNK", 2024a)

4.4.1.1 Prototyping

Since the various concepts use Electrical Gripper, custom fingers had to be designed to be able to pick the connectors, manipulate and pair them with the intended ECU. However, the various concepts required not only a gripper finger to design but also other tools such as a fixture which will be presented later during each concept section. The various designs were carried out in the design software CATIA V5, see Figure 4.6a. These designs were later manufactured in a Fused Deposition Modelling(FDM) printer, see Figure 4.6b, with material Onyx (Markforged, 2024) located in the Smart Factory Lab.



(a) CATIA V5(“CATIA V5 - Dassault Systèmes”, 2024)

(b) Markforged X7, Onyx filament (B.V., 2023)

Figure 4.6: Prototyping

4.4.2 First Iteration

To succeed with the pairing, different design models on grippers fingers were presented. The goal was to make the finger design as adaptable and efficient as possible to avoid collision and pinching with cables during pairing. The first gripper’s fingers presented were to approach the connector from the long sides, see Figure 4.7. This is because the long sides have more surface to expose the connector to pressure during joining where even tiny tolerances between neighbour connectors are respected, see Figure 4.8.

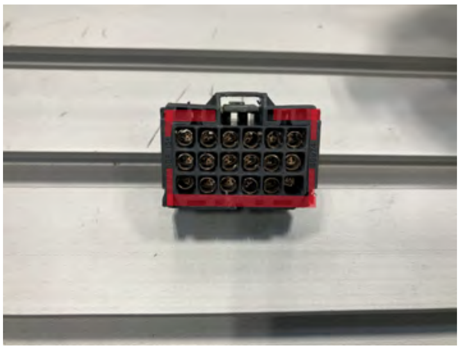


Figure 4.7: Long Sides of Connector(red marked)

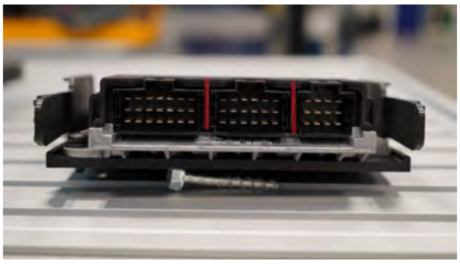


Figure 4.8: Tolerances between Sockets(red marked)

Since the fingers for the long sides would collide with the wall next to where the ECU is placed, see Figure 4.9, it was decided to come up with a different design. Therefore, it was decided to approach the short sides of the connector instead, see Figure 4.10. The only disadvantage of the short sides would be the small surfaces that came to be exposed to pressure during joining. This would possibly lead to the failure of 3D-printed fingers, however not a more robust material such as steel. Based on various trials, fingers were designed that were robust enough to give rise to successful joining.

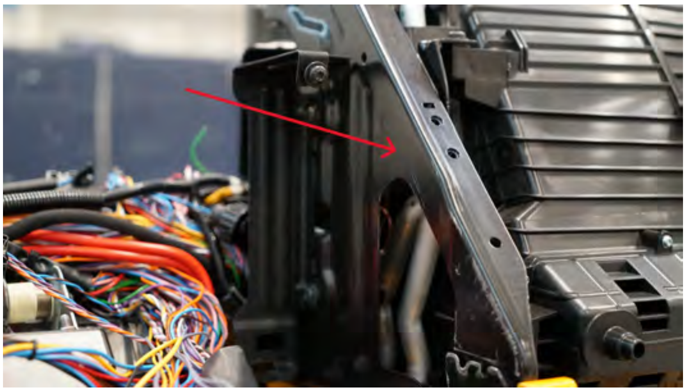


Figure 4.9: Wall Next to ECU CUV3(red arrow)

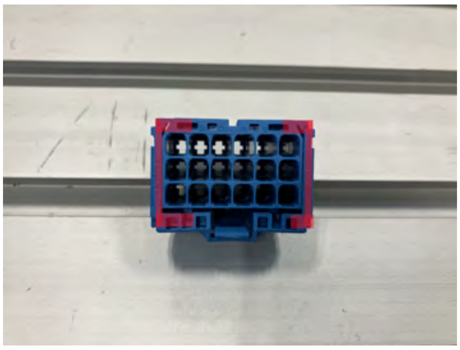


Figure 4.10: Short Sides of Connector(red marked)

Fingers for the short sides were designed in a certain way that respected the neighbouring sockets in ECU CUV3, see Figure 4.11. It also avoided collision with cables during picking and pairing, see Figure 4.12.

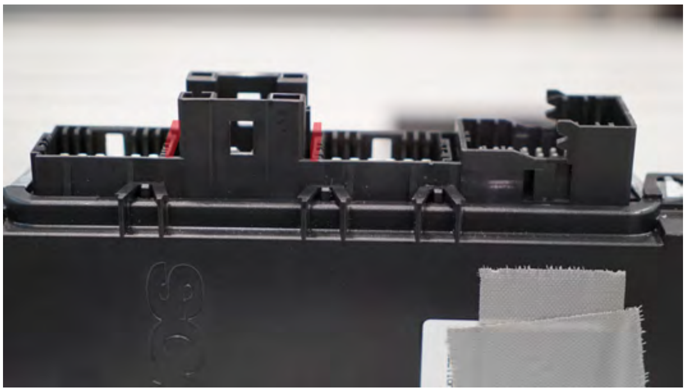


Figure 4.11: Tolerances between Sockets(red marked)

Figure 4.12: Pocket on Fingers

Before testing the various concepts on the Instrument Panel, elementary experiments were performed by only attempting to pair a connector with the ECU. In this phase, only a connector without crimps, see Figure 4.13, were used. The ECU was removed from the instrument panel and locked onto the robot table, see Figure 4.14b.

Figure 4.13: A Silver Crimp used for Grey and Blue Connector

The first experiments was performed in two conditions. First by hardcoding, defining the exact target coordinates for the robot. In this phase the the position of the connector and the socket was defined in the robot programming.

The second condition was done by detecting the connector by a camera and defining the approach target for the robot using the Cambrian vision system. In order to detect the connector the CAD model was sent to Cambrian to get trained. Thereafter the trained model was uploaded to the Cambrian computer and used by the Cambrian camera to get detected, see Figure 4.14.

(a) Grasping **(b)** Joining

Figure 4.14: First Experimentation

4.4.3 Final Concepts

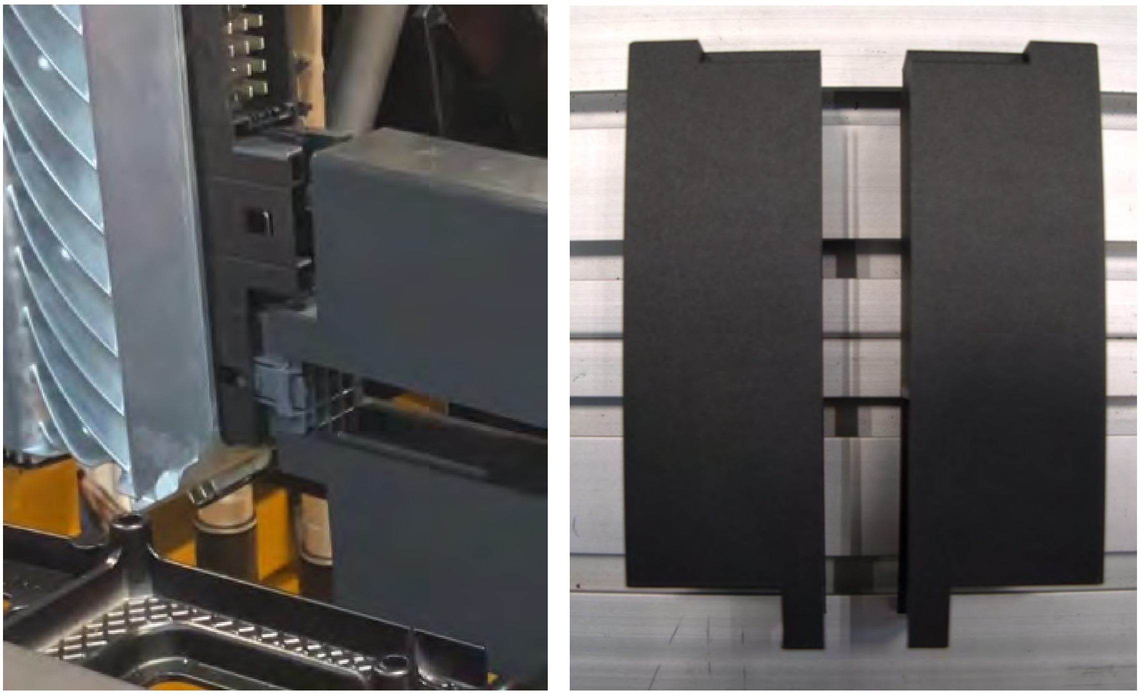
After screening all the concepts in the Elimination Matrix and the Pugh Matrix, the two winning concepts and one discarded were tested and refined. Concept 25 involved human-robot collaboration, while concepts 1 and 13 were fully automatic, i.e. all steps in the assembly process were performed by the robot itself. Concept 13 was split into two sub-concepts due to its complexity. These concepts will be presented in each section in detail.

4.4.4 Concept 25(Human-Robot Collaboration)

Concept Human Robot Collaboration, see Table 4.4, has a human-robot cooperation character since identifying, grasping, manipulating and aligning the connector is carried out by an operator. Joining and confirming joining is done by a UR16 robot where both operator and robot share the same work space but working on different tasks, see Section 3.4. The assembly process is identical to how the work is carried out today by an operator with the only difference being that joining and confirming is carried out by a robot.

The solution was performed by having a team member placing the connector in the target socket after which the robot took over the responsibility of applying pressure to the connector to pair the connector with the ECU for successful pairing.

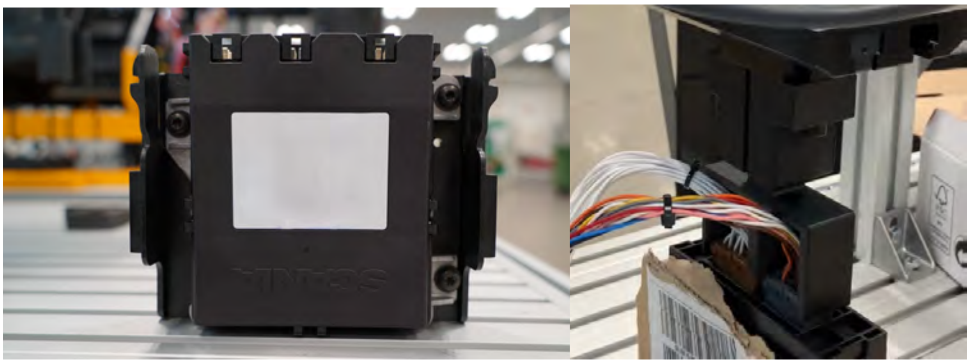
The robot was programmed to define which movements were allowed to be performed and pair the connector with the intended ECU, for instance the exact coordinates were defined for the robot, see Figure 4.15a. Fingers used during this test were similar to fingers used during the first test iterations, however, to avoid collision with the instrument panel and the wall next to the ECU, these were designed with longer arms, see Figure 4.15b. Confirmation of the pairing took place via a force torque sensor that was integrated into the robot itself. In the robot program, a limit of force was set which the robot could not exceed where it was ensured that the pairing was successful and that the ECU and the connector would not be exposed to damage.



(a) Joining the Connector with ECU (b) Long Fingers

Figure 4.15

The solution was tested on another ECU to see if the assembly can be made more efficient. The result was a successful assembly where pairing was performed by placing two connectors in the intended ECUs, see Figure 4.16a, where both connectors were paired with the ECU at the same time. Here, a custom joining tool was designed which was adapted for two connectors of different sizes, see Figure 4.16b

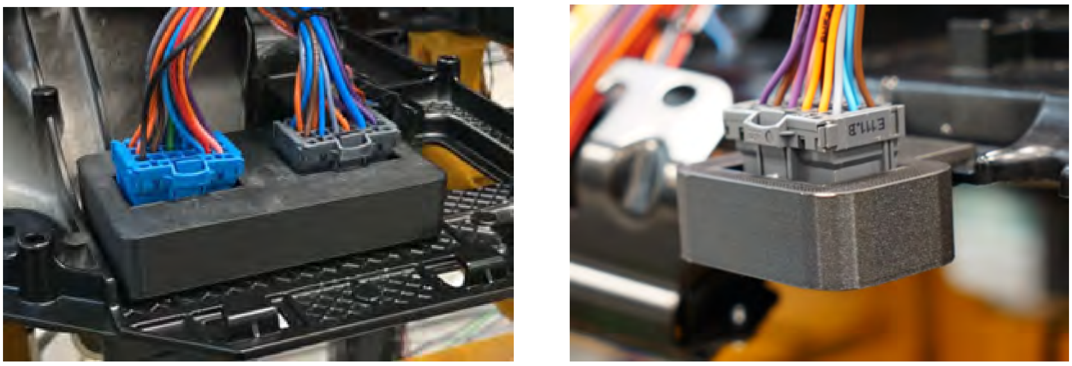


(a) ECU with Three Sockets(Side View) **(b)** Joining Tool for Two Connectors

Figure 4.16

4.4.5 Concept 1(Automatic Static Position)

Concept Automatic Static Position, see Table 4.4, is a fully automatic solution. Here, all assembly steps are performed with the robot. This solution simplifies the process since the cables supplied in bundle and they are scattered in various places. Therefore, the connector was presented in a pre-defined position. To present the connector in a pre-defined position, fixtures of various shapes were designed that could be locked on the instrument panel, see Figure 4.17. Before the assembly process started, the connector was placed in the fixture manually by the team members. The robot was programmed with precise coordinates where the position of the connector and the ECU were predetermined. Although the assembly was a successful result, there were sometimes small deviations. For instance, the ECU could deviate from its predetermined location due to the high tolerances of the locking system. Therefore, the robot's force torque sensor was used to align the connector right into the socket. This was defined in the programming code of the robot.



(a) Two Connectors Storage Fixture **(b)** One Connector Storage Fixture

Figure 4.17: Fixtures

4.4.6 Concept 13

Concept 13, see Table 4.4, had a higher level of complexity because the idea was to approach the connectors with the cables in, just as they were delivered by the supplier. So far, the connector was always approached from the top side, see Figure 4.10, and due to the formlessness of the cables, sometimes twisted around each other, the random position of the connectors which in some cases could lie on top of each other, the high similarity of some connectors and tight spaces in the instrument panel made identification of the intended connector with the camera and access to the top side difficult. Therefore, it was decided that this concept should be further developed, see Table 4.7, into two sub-concepts. The concept was divided into concepts 13a and 13b. Here, the process was simplified by presenting the connector in two different ways.

4.4.6.1 Concept 13a(Automatic Hanging Position)

As it was mentioned in subsection 4.4.6, due to identification difficulties, tight spaces in the instrument panel and difficulty in reaching the top side of the connector, it was decided to present the connector by having it hang outside the instrument panel separate from all other connectors, see Figure 4.18. This facilitated identification of the connector and accessibility to the top side, however, this was possible on the condition that the cables to the connector were long enough for the connector to be outside the instrument panel. At the same time, a manual separation of the connector from the other connectors and cables was required before the start of the assembly process. The purpose of this concept was that the cables should be presented hanging from the supplier from the very beginning, even if one could involve an operator to sort the connectors.

Figure 4.18: Hanging Connector Outside of Instrument Panel

To identify the intended connector and ECU, these were trained by Cambrian employees. The process was that the intended socket in the ECU was first scanned with the camera and the exact coordinates were saved in variables in the robot program. Then the robot did a grid search (a volume where the robot should search to identify an object) to identify the intended connector. The connector was picked with gripper fingers of S-shape, see Figure 4.19. The fingers locked the connector at all degrees of freedom during the intervention. The robot paired the plug with the intended socket and confirmed the pairing using its integrated force toque sensor. The fingers were designed with chamfered edges to guide the connector into its locked position, see Figure 4.20a. Bottom edges were designed to lock the connector in the z-direction, see Figure 4.20b. This solution did not work at first, and after many attempts it was realised that the fault lay in the way the model was trained, the way the fingers were designed, and the way the connector was presented. The cables could come into contact with the fingers or the instrument panel fixture, causing the connector to change position and orientation. Therefore, it was of great importance to present the connector very clearly separated from other objects nearby to have a successful assembly process.

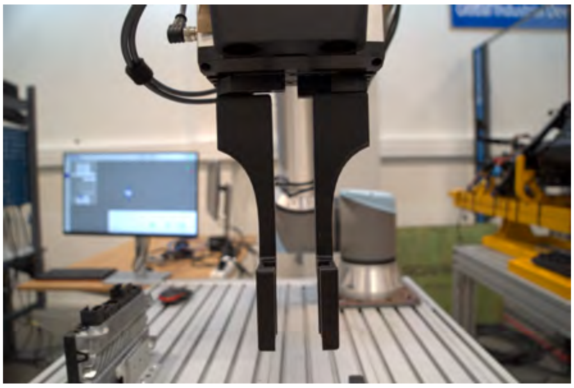


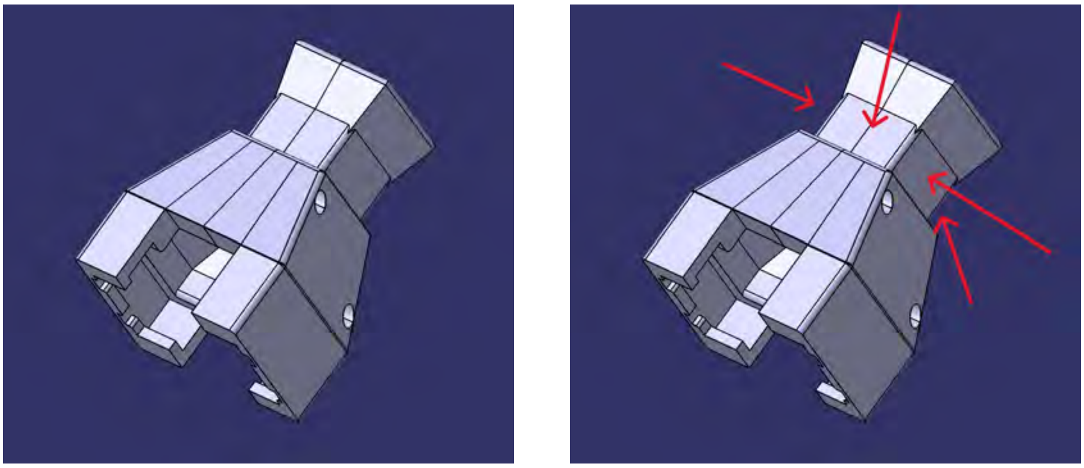
Figure 4.19: S-Shape Fingers

(a) Chamfered Edges(red arrows) **(b)** Locking Edges(red arrows)

Figure 4.20

4.4.6.2 Concept 13b(Automatic Dynamic Position)

Concept Automatic Dynamic Position was largely similar to concept Automatic Hanging Position with only differences in presentation of the connector. The idea was to explore possibilities of approaching the connector exactly as it is delivered from the supplier. As mentioned in Subsection 4.4.6, the connectors and cables were delivered in bundles that were scattered haphazardly, making access to the top side of the connector impossible. Thus, it was suggested that the cables to the connector could be approached instead of top side of the connector. Since the cables are formless, picking the cables was a challenge that needed to be simplified. Due to these circumstances, it was proposed a holder to be mounted on the top side of the connector, see Figure 4.21a. This holder would replace the formlessness of the cables thus increasing the rigidity. The solution would make picking or sorting of cables easier however, it is worth mentioning that this was a suggestion and it was unlikely to always work. The points that would be approached as shown in Figure 4.21b, may come into contact with other objects nearby.



(a) Connector Holder

(b) Picking Points(red arrows)

Figure 4.21

This concept was never tested due to its complexity and lack of time. Here, an AI model needed to be trained that would take into account multiple objects in the camera's grid search. Thus, this concept is left for future research.

4.5 Concept Evaluation

This section focuses on the evaluation of the final concepts developed in the previous section. This step was used to evaluate and find which concepts are more exciting and favourable for further exploration.

4.5.1 Kesselring Matrix

Before initiating the Kesselring Matrix, it is essential to establish the criteria for evaluating the concepts. These criteria will serve as the foundation for assessing each concept's value and effectiveness within the matrix.

The criteria selected from the requirement list for the Kesselring matrix are as follows:

- **Time for operation** - This criterion pertains to the time required for mating a connector to the ECU. A higher score is assigned to concepts that take the lowest time to complete this process and vice versa.
- **Complexity** - This criterion assesses the complexity involved in developing the concept. The scoring for complexity is in reverse, i.e. a higher score of 5 indicates a relatively simple system, while a score of 1 indicates a very complex system.
- **Integration** - This criterion evaluates the ease of integrating the system into the existing assembly line. A higher score indicates that the system will be easier to integrate with the current assembly process and a lower score shows that it is more challenging for integration.
- **Flexibility** - This criterion evaluates the flexibility of the concept in terms of its adaptability to different types of connectors within the wire harness. A higher score indicates greater flexibility, making the concept more versatile and capable of handling multiple variants.
- **Safety** - This criterion evaluates the safety of the concept for human-robot collaboration. A higher score indicates a safer concept.
- **Ergonomics** - This criterion evaluates the ergonomics of the concept. A higher score indicates that the concept is highly ergonomic for operators.
- **Training Requirement** - This criterion reflects the amount of training required for operators to use the concept on the assembly line. A lower score indicates that the concept requires longer and more difficult training and vice versa.

The weights for the criteria were decided using a pairwise comparison matrix as shown in 4.8. The criteria were compared with each other and the values were assigned on the basis of their relative importance. The final weights are in the relative sum column of the table.

Table 4.8: Pairwise comparison matrix for determining weights of the criteria

Criteria		**A**	**B**	**C**	**D**	**E**	**F**	**G**	**Total sum**	**Relative sum**
A	Time for operation	-	1	0.5	0	0	0	0.5	2	0.095
B	Complexity	0	-	0	0	0	0	0.5	0.5	0.024
C	Integration	0.5	1	-	0	0	0	0.5	2	0.095
D	Flexibility	1	1	1	-	0	0	1	4	0.190
E	Safety	1	1	1	1	-	1	1	6	0.286
F	Ergonomics	1	1	1	1	0	-	1	5	0.238
G	Training Requirement	0.5	0.5	0.5	0	0	0	-	1.5	0.071

Some insights from the comparison matrix are:

- **Safety** emerged as the most critical criterion with the highest weight of 0.286. This highlights the paramount importance of ensuring safety, especially as it is the highest priority of the Scania way of working.
- **Ergonomics**, with a weight of 0.238, is the second most important criterion, underscoring the need for ergonomic considerations which were the main focus of the project since the beginning.
- **Flexibility** follows with a weight of 0.190, indicating its significant but comparatively lower importance than safety and ergonomics.
- **Time for Operation** and **Integration (C)** both weigh 0.095, suggesting that they are equally important but less critical than the top three criteria.
- **Training Requirement**, with a weight of 0.071, is considered somewhat important, essentially because it is an explorative thesis.
- **Complexity**, with the lowest weight of 0.024, is deemed the least important criterion in this evaluation because the aim was to explore new technologies that are going to be complex.

After establishing the criteria and their respective weights, each concept was evaluated using the Kesselring Matrix. The evaluation was conducted by assigning scores to each concept based on how well they met each criterion. The scoring system ranged from 1 to 5, with 5 being the best possible score. The weighted scores were then calculated by multiplying the assigned scores with the corresponding weights of the criterion. The final evaluation is shown in Table 4.8. It should be noted that this Kesselring aimed to identify the best concept that could be beneficial for exploring further to improve the ergonomics of the station.

Table 4.9: Kesselring Matrix

Criteria		**Alternatives**							
		Ideal		**1**		**13**		**25**	
Name	**w**	**v**	**t**	**v**	**t**	**v**	**t**	**v**	**t**
Time for operation	0.095	5	0.476	3	0.286	1	0.095	4	0.381
Complexity	0.024	5	0.119	3	0.071	1	0.024	4	0.095
Integration	0.095	5	0.476	2	0.190	4	0.381	2	0.190
Flexibility	0.190	5	0.952	2	0.381	1	0.190	4	0.762
Safety	0.286	5	1.429	2	0.571	4	1.143	1	0.286
Ergonomics	0.238	5	1.190	3	0.714	4	0.952	1	0.238
Training Requirement	0.071	5	0.357	3	0.214	1	0.071	3	0.214
T (Total weighted value)		35	5	18	2.429	16	2.857	19	2.167
T / Tideal		1.00	1.00	0.51	0.49	0.46	0.57	0.54	0.43
Number of weak points		0		3		4		3	
Rank		**0**		**2**		**1**		**3**	

The ideal concept serves as a reference for evaluating the other concepts. After the evaluation, it was identified that, based on the current criteria, concept Automatic Hanging Position is the best concept to be explored further. However, it is not without its drawbacks, as it has the highest number of weak points among all the concepts, totalling four.

In terms of operation time, Concept Human-Robot Collaboration is the most efficient because the operator handles the most time-consuming tasks and does so much faster than the automated setup tested. Concept Automatic Static Position is faster than concept Automatic Hanging Position due to a fixture that provides a fixed location for the robot, eliminating the need for the robot to use a camera to locate the connector, thereby saving time. Regarding complexity, concept Automatic Hanging Position is the most complex, as it requires an identification mechanism, such as a computer vision system, to function. Concepts Automatic Static Position and Human-Robot Collaboration do not require identification technologies. Concept Automatic Static Position is slightly more complex than Concept Human-Robot Collaboration because it requires setting up and removing a fixture position. Concept Human-Robot Collaboration is the simplest, as the robot's sole task is to push the already placed connector.

For integration, Concepts Automatic Static Position and 25(Human-Robot Collaboration) involve Human-Robot Collaboration (HRC), which presents unique challenges for implementation on the assembly line. They require higher safety standards and operator training, making integration more cumbersome compared to having a separate cell where the robot performs the entire operation.

In terms of flexibility, Concept Human-Robot Collaboration is the most adaptable because the operator places the connector into the socket, eliminating many issues related to connector variations. The robot's sole focus is on the task of pushing. For concepts Automatic Static Position and Automatic Hanging Position, the robot needs to pick up the connectors, which significantly reduces flexibility. Concept Automatic Hanging Position is less flexible than Concept Automatic Static Position because, being on the instrument panel, the fingers of the gripper need to be more complex to avoid other components of the harness while picking it up.

When it comes to safety, concept Automatic Hanging Position is the safest because it does not require HRC. Both Concepts 1 and 25(Human-Robot Collaboration) require HRC, but Concept Human-Robot Collaboration is the least safe, as it involves the human coming into the path where the robot will apply the highest force.

In terms of ergonomics, concept Automatic Hanging Position is the best, as it transfers all the unergonomic tasks to the robotic system. Concept Human-Robot Collaboration avoids the most unergonomic task of inserting the connector, but since the operator still aligns the connector to the socket, the wrist can reach inconvenient positions while also having to lift the heavy harness. This is avoided in Concept Automatic Static Position, where the placement of the connector fixture is not nearly as unergonomic.

For training requirements, Concepts Automatic Static Position and Human-Robot Collaboration have similar needs from the operators. The main tasks involve aligning a connector in the assigned position and then having the robot do the pushing or picking, without any complex identification systems. Concept Automatic Hanging Position will require the most training because it has an identification system that the operator needs to understand to work on the station.

Hence, concept Automatic Hanging Position was determined to be the best solution for future development among the evaluated concepts due to its high ergonomics and safety, which are the most crucial criteria. However, significant work is still required to make it ready for implementation on the assembly line.

5

Discussion

In this chapter, the findings from the research and experimentation on the automation of connector mating to improve cable assembly are discussed. This chapter aims to interpret the results in the context of the research objectives and questions outlined in the introduction. The chapter also explores a reflection on the product development process used throughout the thesis.

5.1 Automation in Wire Harness Assembly - Challenges and technologies

Research Question - What are the challenges associated with implementing automation in wire harness assembly (WHA) process?

The assembly of wire harnesses in the automotive industry is predominantly a manual process. At the Oskarshamn factory, the pre-assembly stations for instrument panels do not utilise automated solutions for harness assembly. A review of the SES assessments for these stations revealed that the high required forces during the manual mating of connectors is a significant issue, contributing to unergonomic conditions and increasing the risk of musculoskeletal disorders among operators. Therefore, focusing efforts on testing automation in this process is necessary to enhance ergonomic conditions and reduce health risks for the workforce.

The biggest challenges for implementing automation in the assembly of wire harnesses identified were:

1. **Flexibility and handling of cables:** The cables in the wire harnesses are dynamic, i.e. flexible and lack a fixed orientation during the assembly. It can become entangled within the harness and difficult to assemble. Additionally, the length of the cables can also have a huge impact on the system. The current designs of the harness do not take into account that the cable could be manipulated further than the required length as operators can account for it on the fly, but it is challenging for an automated system to account for it, especially in a complex wire harness. The automated solution must be capable of working with these cables or the design of the harnesses need to be addressed to implement it.

2. **Variety of Connectors:** Wire harnesses in general have a diversity of connectors in terms of their unique shape, size and joining procedure. This poses a challenge of not only identifying the connectors but also developing a unique mechanism for each different joining procedure. The automated solution needs to be adaptable to tackle this issue.

3. **Accuracy and Precision:** The picking and joining requires a precise system as the connectors are surrounded by other connectors and cables on the assembly product. In the present ECU, the connectors have only a few millimetres of clearance for mating. This is not a problem for operators as they use their senses to feel the correct mating, but for an automated solution, this will create complexity.

4. **High Forces for mating:** The mating force, which can sometimes exceed $130N$, poses a significant ergonomic challenge for human operators and also presents concerns for automated solutions. Applying these high forces in multiple orientations requires a robust system capable of precise directional force application. This requirement often exceeds the capabilities of many collaborative robots. Additionally, the system must apply force accurately to avoid damaging the socket and surrounding components.

5. **Constrained product design:** The product on which the wire harness assembly is mounted typically has significant constraints. The harnesses follow a very compact and intricate path, and the ECUs must fit into tight and narrow spaces. These factors make designing an automated solution that can move within the product extremely challenging.

6. **Integration:** The integration of an automated solution on the assembly line involves many technical and safety challenges. If the automated solution includes Human-Robot Collaboration (HRC), it must undergo careful testing and approval processes. Additionally, there are concerns about the automated solutions being slower than human operators, the initial cost of deploying such systems and the need for extensive retraining of staff.

Research Question - What technologies are being developed and explored for mating connectors in wire harness assembly?

There has been considerable recent research in the field of manufacturing and assembling wire harnesses. Throughout this thesis, several technologies were identified through both interviews and literature reviews. These technologies, when implemented, have the potential to significantly enhance the efficiency of automated solutions. Some of the most notable technologies identified include:

- **Human-Robot Collaboration (HRC):** HRC combines the adaptability and dexterity of operators with the strength and repetitive accuracy of a robot. Cobots can now be equipped with sophisticated sensors, improved interfaces, and easier integration capabilities. These advancements lower the barriers to entry, making cobots more accessible and versatile. They can also incorporate advanced adaptive systems such as computer vision and adaptive learning algorithms, enabling them to efficiently manage variations in the assembly process.

- **Advanced Grippers:** Recent advancements in grippers have led to the development of new electrical grippers that offer precise control over speed, position, and force. This precision is crucial for handling various types of connectors without causing damage to them. Most grippers support custom-made fingers, allowing the development of designs that could adapt to different connector variations effectively.

- **Computer Vision Systems:** These systems enable automated solutions to interpret environments similarly to humans, which is advantageous in assembly processes originally designed for human operators. They use camera systems and advanced machine-learning techniques to identify objects. Some systems incorporate stereo vision or depth cameras, providing essential depth information. They can identify, align, and give precise coordinates to the robotic system as needed. Novel systems, such as the one used in the Cambrian system discussed in this thesis, utilise only the 3D CAD file of the object to directly provide exact pick points to the robot after positive identification. These systems are not only employed for object recognition, alignment, and navigation but also for performing quality checks. The speed of these camera systems also has significantly increased, enhancing the efficiency of the automation process. The Cambrian system, for instance, can make precise predictions and identify parts within just 0.2 seconds, facilitating rapid and accurate operations.

- **Peg-in-hole strategy:** The peg-in-hole strategy is developed for guiding objects into a hole, which makes it ideal for connector mating operations (Sun et al., 2010). This strategy leverages force-torque sensors to provide real-time feedback on the forces applied during insertion, allowing the system to make adjustments to avoid damaging delicate components. Camera systems can also be employed to offer visual feedback, either by aligning the components before mating or monitoring the process during insertion. By integrating multiple sensors, such as force-torque and vision systems, the mating process can be significantly enhanced, ensuring greater precision and reliability.

5.2 Discussion on the Setup

Research Question - What kind of a collaborative setup is best suited for mating of connectors?

Concept Human-Robot Collaboration not least solves the ergonomic problem but has great possibilities for implementation since this concept has a cooperation level of collaboration. This is because the complexity of the execution of this concept is low. In this concept, all randomness is respected since the sorting and identification of connectors and cables is performed by a human, thus the risk of failure is less. This concept does not require vision systems and can be programmed for specific purposes. The best arrangement for this concept would be simultaneous multi-assembly of connectors to increase efficiency in a separate station where assembly is carried out completely before it is sent on to the line for the remaining tasks and also the flexibility of the system where the human can control the robot when deviations occur. However, the disadvantage is that the concept is not fully automatic and always requires at least one person involved for the assembly to be successful. This means that a person will continue to be exposed to physical stress while performing the first steps more or less.

Concept Automatic Static Position is extremely dependent on specific conditions to be successful. This means that connectors must always be presented to the robot in a specific location where they are reachable and can be picked up. It must also be clearly stated which connector is to be handled and the ECU must always have a more stable locking system where it does not change position after each assembly. This is to ensure the execution of the assembly process. How the connectors should be presented, for example in a fixture as a predetermined position, is something that can be handled by the supplier or by those responsible in R&D. The setup must be in a way that the robot arm can reach its goals both during picking and manipulation but also during pairing without any collision occurring.

Concept Automatic Hanging Position was possible under the circumstances that the connector is separated from all other connectors and cables where it is reachable. In this case collision is avoided and identification is more successful during picking. The cables must be long enough to ensure safety and successful pairing. A good setup could be that a hanging connector is larger where the edges around the connector are free of objects, which improves picking success. This also increases the assurance that a connector is locked in all degrees of freedom.

Since the concept Automatic Dynamic Position aims to approach the cables exactly as delivered by the supplier, even if it was never tested, the proposal here is an increased stiffness of the cables as a solution. For instance, a channel of tube over the wires that go into the connector would provide more rigidity that would facilitate sorting and picking of the connector or cables.

5.3 Design of Gripping Mechanism

Research Question - How should grippers be designed for robotic systems to effectively pick up connectors?

The design of the gripping mechanism is essential for ensuring successful mating operation from the picking of the connector to insertion in the socket. The key components of the gripping mechanism are the gripper and the fingers.

Some design guidelines identified for developing a good gripping system for an automated solution for WHA focusing on the mating operation are:

- **Gripper**
  - **Position Control:** Position control in a gripper is vital to accurately engage different variants of connectors without causing damage. It also aids in the precise disengagement of the connector after insertion, preventing collisions with other components.
  - **Force Control:** A gripper with force control is essential for engaging connectors without deforming or damaging them. This ensures that the correct amount of force is applied for secure and safe handling.
  - **Quick change mechanism:** Implementing a quick change mechanism in the gripper is beneficial for rapidly switching between different fingers, especially in the assembly of complex products with multiple connector variants. This will significantly reduce assembly time on the production line.
  - **High Compatibility:** Ensuring the gripper is compatible with different robot manufacturers facilitates easy integration and future-proofs the investment.
- **Fingers**
  - **Fit a family of connectors:** The fingers should be designed to accommodate a family of connectors rather than a single connector. During the thesis, it was observed that connectors typically belong to a family with shared design features, such as width. This allows multiple connectors to be handled using the same gripper fingers.
  - **Clearance:** The fingers should be designed to avoid collisions within the confined spaces of the product when the robotic system is in motion. Proper clearance also ensures smooth operation and secure engagement of the connector without causing damage to it.
  - **Aligning features:** The fingers should have aligning features that facilitate the engagement of the connector. These features can be in the form of chamfers, fillets or other guiding mechanisms that ensure the proper alignment. These features can also compensate for the lower accuracy of the identification system, if any increasing the robustness of the system.
  - **Soft tips:** Incorporating a soft gripping surface on the finger where the connector is engaged helps avoid damaging the connector surfaces. Connectors are generally made of plastic, making them brittle and prone to scratches and breakage. The connectors used in the experiments for the

  setup were damaged when using 3D-printed fingers.

  - **Modular design:** Developing a modular design for the fingers is recommended. This is useful for assemblies involving multiple families of connectors and allows for adjustments in finger length or tilting to reach sockets effectively.

5.4 Design guidelines for the Product

Research Question - What design guidelines can be derived from the tests and experiments for products that include wire harnesses to facilitate the integration of automated wire harness assembly process?

The design of the product on which the WHA will be performed, specifically the connectors and the instrument panel in this thesis, is crucial to enable and enhance automation in the assembly line. This aligns with the principles of Design for Automated Assembly (DFAA), which emphasise designing components and systems to simplify and facilitate automation. These guidelines are intended to augment existing DFAA principles with the insights gained from this thesis.

The guidelines are:

- **Reduce the number of connectors and variants:** When designing the product, it is important to minimise or, ideally, standardise the types of connectors by using a single family of connectors or selecting a set with similar physical characteristics. This approach helps reduce the complexity of finger designs.

- **Prominent Grasp points on the connector:** One of the major challenges identified during the experimentation phase was the lack of suitable grasping positions on the connector. This complication made the design of the finger more difficult and increased the risk of damaging both the connector and the socket. To address this issue, it is essential to design connectors with well-defined grasping points. These grasping points should be strategically positioned to ensure secure handling by robotic grippers without interfering with the connectors' functionality or compromising their structural integrity.

- **Self-aligning features:** The connector and the socket should have self-aligning features that facilitate the insertion allowing automatic alignment and reducing the need for high-precision positioning of the system.

- **Ensure the stability of the Socket:** During the experimentation phase, it was found that none of the ECU mounts on the instrument panel could adequately withstand the force required for connector insertion. Ensuring that the socket is securely fixed, especially in the direction of mating, will prevent unnecessary movement during the insertion process. This stability will facilitate easier insertion for the automated solution and result in a more robust system.

- **Robotic workspace allowance:** Ensuring there is adequate space for robotic operation is crucial for the efficient functioning of automated systems. Currently, the instrument panel does not have enough space for the robot arm to move around and it creates a difficulty to find a path that works best. This involves designing the layout of the product and surrounding areas to provide sufficient clearance for the gripper system to move freely without obstruction to the socket. Adequate workspace allowance helps prevent collisions and enables the robot to perform precise movements required for connector mating.

- **Structured Presentation of the Harness on the Product:** During the concept evaluation phase, it was identified that presenting a cable in a predefined manner, using a fixture or predetermined position, significantly enhances the speed and robustness of the robotic system. This approach prevents cable tangling and provides ample space for picking the connector without displacing other cables in the harness.

- **Cable length:** Cables should be designed with positive tolerance to ensure they are not too short. While a human operator can adapt to shorter cables by adjusting their working methods, this adaptability is too complex for an automated solution. Therefore, the cable length should be considered for the product dimensions and the additional movements required by an automated system to avoid other cables. Ensuring adequate cable length will facilitate smoother operations and reduce the risk of errors or damage during assembly. Additionally, cables with sufficient length allow for greater flexibility in the layout of the assembly process, enabling more efficient routing and connection by robotic systems.

5.5 Reflection on the Process

The process followed for this thesis was inspired by Ulrich et al., 2019 and the Product Development project course taken by the team at Chalmers University of Technology. Given the exploratory nature of the project, adhering to a rigid product development strategy was challenging. The approach needed to be flexible to accommodate the evolving project scope, which is why the agile methodology proved effective. Weekly meetings with supervisors from Scania helped in weekly goal setting, allowing the project to progress smoothly.

Initially, formulating the research questions was difficult due to the shifting scope of the project in the first month. There was confusion between focusing on solving the ergonomic issues at the station or prioritising the implementation of automation. Ultimately, the focus was directed towards automation, aligning with the objectives of the EWASS project to explore modern technologies for addressing ergonomic problems in wire harness assembly.

A project plan was created and followed during the initial research phase. However, it required constant updates due to delays in the arrival of parts, changes in the logistics of the Oskarshamn visit and the experimentation period. The risk analysis performed at the beginning proved helpful throughout the project, but it would have been more beneficial if it had been updated continuously.

Despite significant new research literature on automation in manufacturing wire harnesses, the literature study was challenging due to the limited research specifically on the automation of wire harness assembly in final products.

Identifying customer needs was one of the most significant challenges during the thesis. Setting a requirement list with strict target values was difficult as the project explored new technologies and methods. Only the ergonomic requirements had exact values derived from the SES standard, while other criteria were based on desires and subjective opinions from interviews.

The function-means tree was used to identify the sub-functions of the setup. This tool was instrumental in breaking down the problem into smaller, manageable parts. The morphological matrix was developed using the Morpheus tool (Martinsson Bonde et al., 2022), which proved highly useful. The tool allowed for defining incompatibilities among solutions, enabling or disabling individual solutions, and employing different strategies for developing the concept catalogue. These features helped narrow down the solution space and facilitated faster concept screening. The ability to export data to a CSV file was beneficial for preserving the concept catalogue.

For the elimination matrix, only the ergonomic requirements could be strictly considered. In hindsight, the elimination matrix could have been skipped entirely and incorporated within the morphological using the Morpheus tool, as the eliminated concepts often shared a common solution that could have been identified earlier. This would have streamlined the concept screening process further. The Pugh matrix was then applied to the remaining concepts. As previously mentioned, identifying criteria was challenging; therefore, most criteria were based on desires. The focus was on comparing the concepts to find the best automated solution that could be tested in the lab with existing equipment or with minimal additional orders. In retrospect, more criteria could have been used, but the criteria chosen were sufficient to identify the final concepts. During the Pugh matrix screening, small test setups were created to evaluate individual components of the concepts. This included using a camera to identify the connector housing without the cable, testing if the robot could push in the connector, and finding the best gripper for the concepts.

After identifying the concepts, a test setup was prototyped that incorporated all the concepts on a single test bench. The test-design-build strategy proved valuable in this phase, accelerating development, particularly for creating different types of gripper fingers. Instead of aiming for the perfect gripper in one attempt, multiple iterations with small adjustments were conducted, fully leveraging the benefits of rapid prototyping. This iterative approach allowed for quicker identification of the optimal gripper finger while uncovering other previously unconsidered aspects.

During this phase, constant communication with Cambrian Robotics was maintained to develop the best computer vision model capable of accurately identifying the connector with the cables and obtaining the optimal model of the ECU. However, significant time was invested in perfecting the model and awaiting subsequent iterations. Additionally, considerable time was spent securing a non-disclosure agreement (NDA) between Scania and Cambrian to facilitate the sharing of the CAD files of the ECU. This caused substantial delays in the evaluation process.

In conclusion, the process followed in this thesis emphasised exploration, flexibility, and speed. The tools used proved effective, although some adjustments to the process could further enhance its efficiency.

6

Conclusion

The conclusion can be drawn that both the ergonomic challenge for the operator and the implementation of automation in cabling assembly were successfully solved, however, in simplified circumstances. Based on the results achieved during the project, it could be concluded that automation of cables is not possible on the current instrument panel with the setups tested. However, the instrument panel could be designed with the help of the design team using the guidelines mentioned in the previous chapter for automatic assembly to be feasible. This is because automation is more limited in its movements and size, unlike manual assembly.

In addition, for future exploration of a fully automatic system, it is recommended to add an extra robot arm where two robots collaborate to facilitate sorting the cables when presented dynamically and as a result more successful assembly. Moreover, the system can be strengthened with a smarter vision system that takes all variations, different connectors and cables/cable lengths with different finger designs, in the process into consideration.

Although the goal of the project was not implementation but exploration of the problem, stakeholders are advised to look more closely at technologies that exist further in the future. There may be opportunities to completely replace cables in the future with a wireless system. Disregarding the art aspect in the current price situation, Humanoid robots can be recommended to be researched more in the future. Even investing resources in a more optimized vision system would improve the assembly process.

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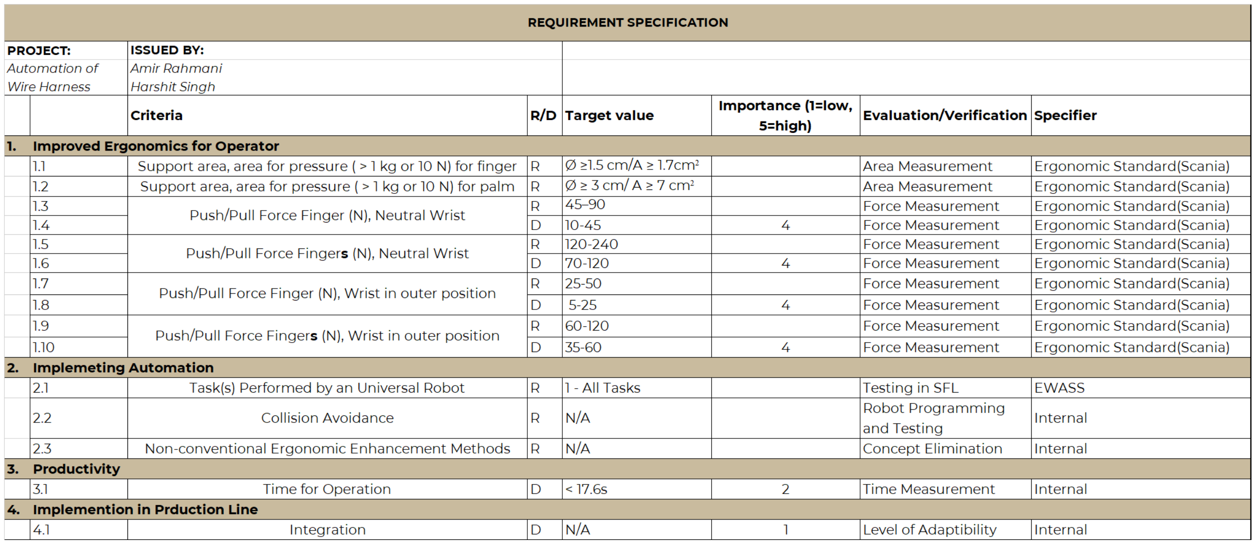
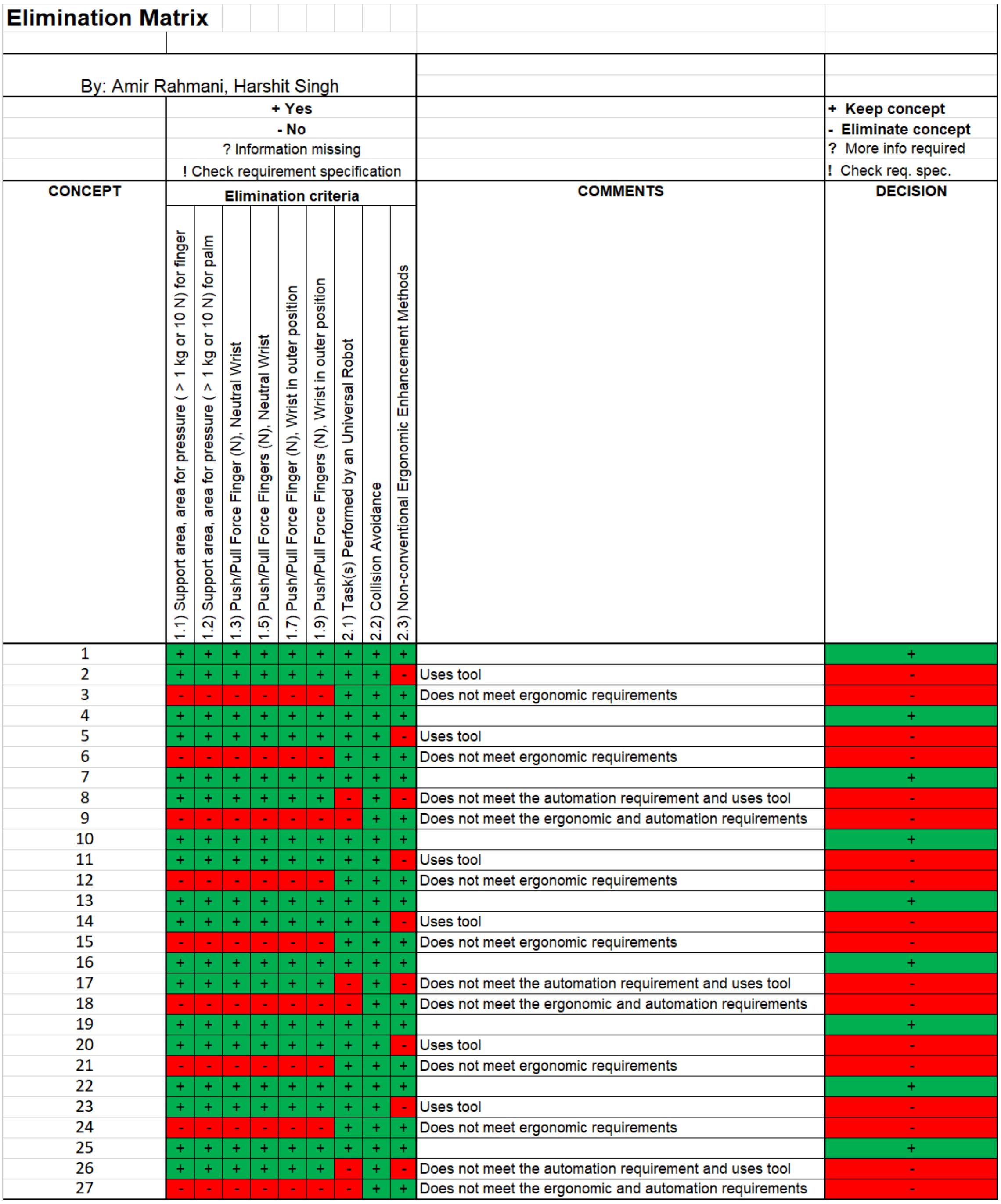
A
Appendix

A.1 Requirement List



REQUIREMENT SPECIFICATION							
PROJECT: *Automation of Wire Harness*		**ISSUED BY:** *Amir Rahmani* *Harshit Singh*					
		Criteria	**R/D**	**Target value**	**Importance (1=low, 5=high)**	**Evaluation/Verification**	**Specifier**
1.	**Improved Ergonomics for Operator**						
	1.1	Support area, area for pressure (> 1 kg or 10 N) for finger	R	Ø ≥1.5 cm/A ≥ 1.7cm^2		Area Measurement	Ergonomic Standard(Scania)
	1.2	Support area, area for pressure (> 1 kg or 10 N) for palm	R	Ø ≥ 3 cm/ A ≥ 7 cm^2		Area Measurement	Ergonomic Standard(Scania)
	1.3	Push/Pull Force Finger (N), Neutral Wrist	R	45–90		Force Measurement	Ergonomic Standard(Scania)
	1.4		D	10-45	4	Force Measurement	Ergonomic Standard(Scania)
	1.5	Push/Pull Force Finger**s** (N), Neutral Wrist	R	120-240		Force Measurement	Ergonomic Standard(Scania)
	1.6		D	70-120	4	Force Measurement	Ergonomic Standard(Scania)
	1.7	Push/Pull Force Finger (N), Wrist in outer position	R	25-50		Force Measurement	Ergonomic Standard(Scania)
	1.8		D	5-25	4	Force Measurement	Ergonomic Standard(Scania)
	1.9	Push/Pull Force Finger**s** (N), Wrist in outer position	R	60-120		Force Measurement	Ergonomic Standard(Scania)
	1.10		D	35-60	4	Force Measurement	Ergonomic Standard(Scania)
2.	**Implemeting Automation**						
	2.1	Task(s) Performed by an Universal Robot	R	1 - All Tasks		Testing in SFL	EWASS
	2.2	Collision Avoidance	R	N/A		Robot Programming and Testing	Internal
	2.3	Non-conventional Ergonomic Enhancement Methods	R	N/A		Concept Elimination	Internal
3.	**Productivity**						
	3.1	Time for Operation	D	< 17.6s	2	Time Measurement	Internal
4.	**Implemention in Prduction Line**						
	4.1	Integration	D	N/A	1	Level of Adaptibility	Internal

A.2 Elimination Matrix



Elimination Matrix

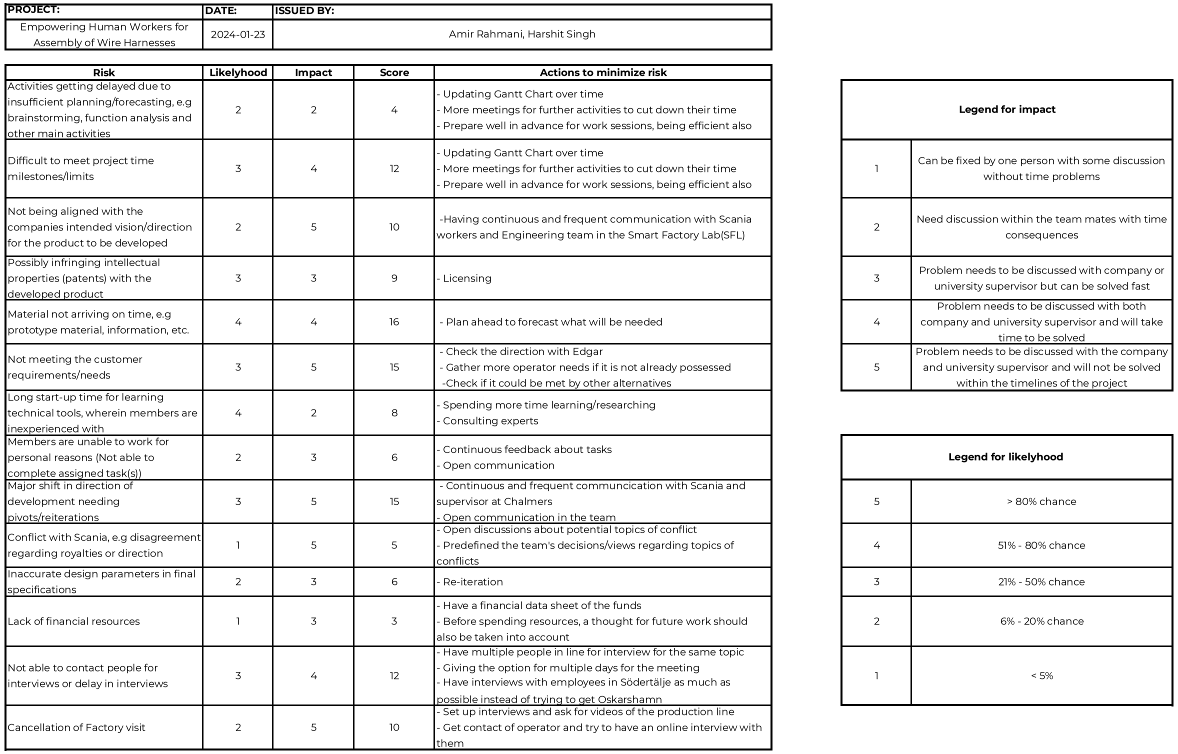
By: Amir Rahmani, Harshit Singh

+ Yes
- No
? Information missing
! Check requirement specification

+ Keep concept
- Eliminate concept
? More info required
! Check req. spec.

CONCEPT	**Elimination criteria** 1.1) Support area, area for pressure (> 1 kg or 10 N) for finger	1.2) Support area, area for pressure (> 1 kg or 10 N) for palm	1.3) Push/Pull Force Finger (N), Neutral Wrist	1.5) Push/Pull Force Fingers (N), Neutral Wrist	1.7) Push/Pull Force Finger (N), Wrist in outer position	1.9) Push/Pull Force Fingers (N), Wrist in outer position	2.1) Task(s) Performed by an Universal Robot	2.2) Collision Avoidance	2.3) Non-conventional Ergonomic Enhancement Methods	**COMMENTS**	**DECISION**
1	+	+	+	+	+	+	+	+	+		+
2	+	+	+	+	+	+	+	+	-	Uses tool	-
3	-	-	-	-	-	-	+	+	+	Does not meet ergonomic requirements	-
4	+	+	+	+	+	+	+	+	+		+
5	+	+	+	+	+	+	+	+	-	Uses tool	-
6	-	-	-	-	-	-	+	+	+	Does not meet ergonomic requirements	-
7	+	+	+	+	+	+	+	+	+		+
8	+	+	+	+	+	+	-	+	-	Does not meet the automation requirement and uses tool	-
9	-	-	-	-	-	-	-	+	+	Does not meet the ergonomic and automation requirements	-
10	+	+	+	+	+	+	+	+	+		+
11	+	+	+	+	+	+	+	+	-	Uses tool	-
12	-	-	-	-	-	-	+	+	+	Does not meet ergonomic requirements	-
13	+	+	+	+	+	+	+	+	+		+
14	+	+	+	+	+	+	+	+	-	Uses tool	-
15	-	-	-	-	-	-	+	+	+	Does not meet ergonomic requirements	-
16	+	+	+	+	+	+	+	+	+		+
17	+	+	+	+	+	+	-	+	-	Does not meet the automation requirement and uses tool	-
18	-	-	-	-	-	-	-	+	+	Does not meet the ergonomic and automation requirements	-
19	+	+	+	+	+	+	+	+	+		+
20	+	+	+	+	+	+	+	+	-	Uses tool	-
21	-	-	-	-	-	-	+	+	+	Does not meet ergonomic requirements	-
22	+	+	+	+	+	+	+	+	+		+
23	+	+	+	+	+	+	+	+	-	Uses tool	-
24	-	-	-	-	-	-	+	+	+	Does not meet ergonomic requirements	-
25	+	+	+	+	+	+	+	+	+		+
26	+	+	+	+	+	+	-	+	-	Does not meet the automation requirement and uses tool	-
27	-	-	-	-	-	-	-	+	+	Does not meet the ergonomic and automation requirements	-

A.3 Risk Analysis



PROJECT:	DATE:	ISSUED BY:
Empowering Human Workers for Assembly of Wire Harnesses	2024-01-23	Amir Rahmani, Harshit Singh

Risk	Likelyhood	Impact	Score	Actions to minimize risk
Activities getting delayed due to insufficient planning/forecasting, e.g brainstorming, function analysis and other main activities	2	2	4	- Updating Gantt Chart over time - More meetings for further activities to cut down their time - Prepare well in advance for work sessions, being efficient also
Difficult to meet project time milestones/limits	3	4	12	- Updating Gantt Chart over time - More meetings for further activities to cut down their time - Prepare well in advance for work sessions, being efficient also
Not being aligned with the companies intended vision/direction for the product to be developed	2	5	10	-Having continuous and frequent communication with Scania workers and Engineering team in the Smart Factory Lab(SFL)
Possibly infringing intellectual properties (patents) with the developed product	3	3	9	- Licensing
Material not arriving on time, e.g prototype material, information, etc.	4	4	16	- Plan ahead to forecast what will be needed
Not meeting the customer requirements/needs	3	5	15	- Check the direction with Edgar - Gather more operator needs if it is not already possessed -Check if it could be met by other alternatives
Long start-up time for learning technical tools, wherein members are inexperienced with	4	2	8	- Spending more time learning/researching - Consulting experts
Members are unable to work for personal reasons (Not able to complete assigned task(s))	2	3	6	- Continuous feedback about tasks - Open communication
Major shift in direction of development needing pivots/reiterations	3	5	15	- Continuous and frequent communcication with Scania and supervisor at Chalmers - Open communication in the team
Conflict with Scania, e.g disagreement regarding royalties or direction	1	5	5	- Open discussions about potential topics of conflict - Predefined the team's decisions/views regarding topics of conflicts
Inaccurate design parameters in final specifications	2	3	6	- Re-iteration
Lack of financial resources	1	3	3	- Have a financial data sheet of the funds - Before spending resources, a thought for future work should also be taken into account
Not able to contact people for interviews or delay in interviews	3	4	12	- Have multiple people in line for interview for the same topic - Giving the option for multiple days for the meeting - Have interviews with employees in Södertälje as much as possible instead of trying to get Oskarshamn
Cancellation of Factory visit	2	5	10	- Set up interviews and ask for videos of the production line - Get contact of operator and try to have an online interview with them

Legend for impact	
1	Can be fixed by one person with some discussion without time problems
2	Need discussion within the team mates with time consequences
3	Problem needs to be discussed with company or university supervisor but can be solved fast
4	Problem needs to be discussed with both company and university supervisor and will take time to be solved
5	Problem needs to be discussed with the company and university supervisor and will not be solved within the timelines of the project

Legend for likelyhood	
5	> 80% chance
4	51% - 80% chance
3	21% - 50% chance
2	6% - 20% chance
1	< 5%

Figure A.1: Risk Analysis of the Project

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