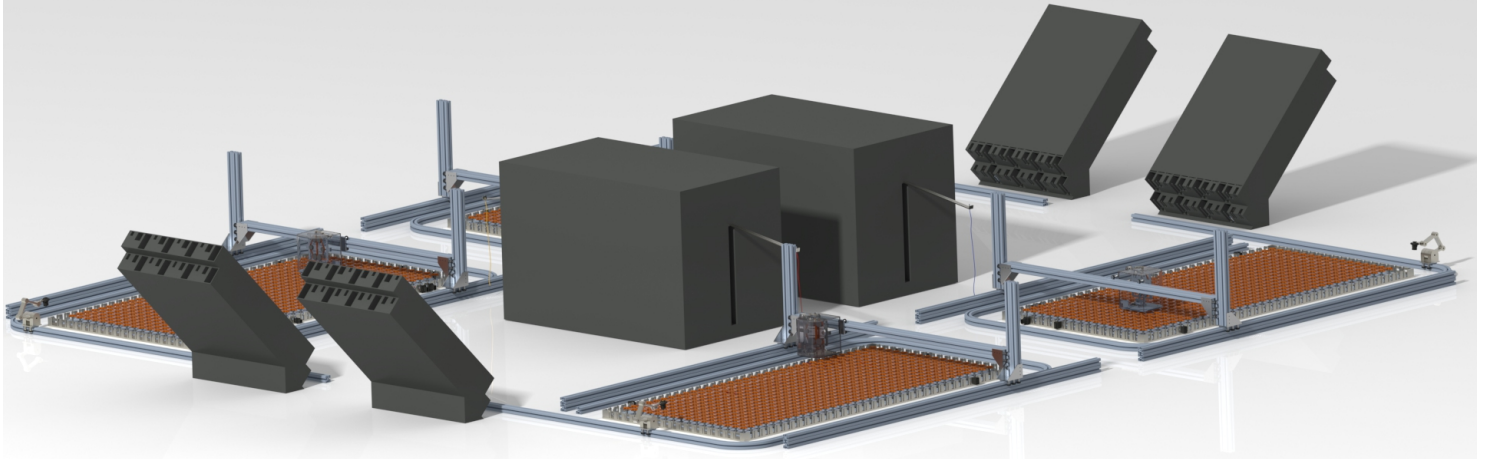




CHALMERS



Design of an Automated Wiring Harness Manufacturing Machine

Product development and impact assessment of a novel manufacturing system

Masters's thesis in Product Development

Jonatan Liesén Gullmander
Oliver Márkus-Johansson

DEPARMENT OF MECHANICAL ENGINEERING

CHALMERS UNIVERSITY OF TECHNOLOGY
Göteborg 2026
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MASTER'S THESIS 2026

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Cover picture: A computer rendering depicting several instances of the resulting solution for the wiring harness manufacturing machine.

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Abstract

The increasing smartification of vehicles, including heavy vehicles like trucks leads to greater demands and higher complexity when it comes to the vehicle's nerve system; electrical wiring. Supplying low-voltage and signals, wiring harnesses experience high variation due to the practically endless truck configurations. This, combined with a high level of manual manufacturing makes wiring harnesses among the most expensive components of a truck.

Current manual manufacturing methods were found to be costly both operationally and during product changes. Addressing this, previous attempts at automation of harness manufacturing have either not proceeded past the patenting stage, or not included manufacturing of chassis harnesses, that require additional operations like adding of protections. This thesis examines relevant literature and seeks to develop an automated manufacturing solution from the ground-up, supported both by established product development methods like functional decomposition tree, morphological matrix, elimination matrix, and Pugh matrix, and practical test-design-build cycles with an emphasis on early testing with rapid prototyping.

The development process resulted in a modular and expandable manufacturing system capable of manufacturing selected signal harnesses. In addition, the thesis explores what impact the widespread implementation of the automated solution would have on the wider manufacturing process, wiring engineering, ethical areas, and on the economics of the company were such a system is implemented. The findings are discussed and recommendations for automation are presented, including component standardisation, design for automation, and technology leadership.

Keywords: wiring, harness, manufacturing, automotive, production, automation, electrical, connectivity

Preface

The purpose of this thesis is not to analyse various automation scenarios or to determine the division of tasks between man and machine, but rather to move the needle forward in a concrete, practical way. The thesis does not propagate from the question “What should be done?”; many papers have answered that question. Rather, we would like to find out “How could it be done?” in a very concrete and practical way. And if it could be done; “How would this impact the lives of the people in this industry?”

The thesis topic was outlined during the summer of 2025, while one of the authors was working a summer job at the Wiring Harness group at Volvo TTI. The idea was to automate the highly manual and costly manufacturing of wiring harnesses, which has a significant cost impact on the total truck cost and on the work of the wiring engineers. Apart from demonstrating the technical feasibility of an eventual solution, the economic viability was also thought to be required for further development of this idea to be seriously considered. Thus, these two parts were recognised as the main focus of the thesis, with several other parts being added that would support this.

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Additionally, we would like to thank Hao Wang at SII-Lab for giving us a tour of the lab and insights into ongoing harness-related research and would also want to thank Peter Öhman at LinQ by Quakka for the opportunity to observe harness manufacturing in practice, and for Gustav Täng and Erik Marklund for setting up this opportunity.

Lastly, we would like to thank all the wiring engineers, cost engineers, quality engineers, and technicians at Volvo TTI Lundby for being so open and helpful. This thesis would not have been possible without all of you.

Jonatan Liesén Gullmander,
Oliver Márkus-Johansson,

Göteborg, June 2026

Acronyms

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

Acronym	Stands for	Explanation
CAN	Closed Area Network	Serial communication protocol, here used for exchanging signals between truck ECUs
CNC	Computer Numerical Control	Method of controlling a motorised tool with a computer according to specific instructions
DLO	Deformable Linear Object	Description of a flexible, long object such as a wire
DLPS	Dual Layer Protection System	Type of woven harness wrapping, either in a sleeve or tape format
DSM	Dependency Structure Matrix	In this thesis, a method used for optimally restructuring process operations based on dependencies between these
ECU	Electronic Control Unit	Generic name of an electronic component that controls certain truck functions
HDSCS	Heavy Duty Sealed Connector Series	A connector family by TE
OEM	Original Equipment Manufacturer	In this thesis, referring to any company under Volvo Group
PCR	Product Change Request	A request by the OEM to the supplier to apply changes to their product
WH	Wiring Harness(es)	

Wiring Harness Components and Terminology

Wire

A wire is a single conductor covered with insulation. Unlike a cable, a wire is not intended to distribute electrical current or signals across multiple conductors.

Cable

A cable is a single wire or a group of two or more wires, which may be arranged in parallel, twisted, or shielded configurations, used to distribute electrical current or signals.

Wiring harness

A wiring harness is a group of wires and/or cables bundled together to connect the contact points of one or more electrical components. A single wire can also be considered a wiring harness if additional operations, such as adding tape, terminals, or conduit, are applied.

Terminal

A terminal is a metallic component attached to a wire, used to connect to a mating part and distribute electrical current. Some terminals are designed to fit into each other and are classified as male or female.

Connector

A connector is a housing with assembled wire terminals used to join wires or cables to an electrical device.

Housing

A housing is the connector part without terminals. Housings can be male or female, which refers to the housing itself and not to the terminals. A housing can have multiple cavities of varying size that enable the insertion of terminals.

Free end

A free end is a wire end without any terminal attached. It can be blunt cut with insulation intact, semi-stripped with part of the conductor exposed, or fully stripped with the conductor completely exposed.

Splice

A splice is a connection between two or more wires that allows electrical current or signals to pass between them. Splices are typically made by crimping or soldering and are used to join wires without a connector.

Prepared wire

A prepared wire is a wire with all active components installed and which has been prepared for insertion into connector housings. A prepared wire has no free ends and has all necessary active components installed such as terminals, grommets and wire level insulation, along with necessary operations such as splicing.

Wrappings

All passive components that are used to protect (or “wrap”) the wires of a harness, such as corrugated tubes, DLPS, jackets and housings.

DLPS

Dual-layer protection system is a thin, fabric-like woven wrapping that comes in a sleeve or tape format. It is used as a lightweight and flexible protection for chassis harnesses.

Jacket

A jacket is the outermost material, usually an extruded plastic or elastomer, applied to one or more wires to provide mechanical and environmental protection.

Corrugated tubes

Corrugated tubes are used as a wrapping around wires to protect these against chafing in chassis harnesses.

Grommet

A grommet is used around the end of a wire and before the terminal, to seal the space between the connector housing and the wire to prevent water intrusion into the connector interface. Often, the grommet is secured to the top of the terminal by means of crimping.

Plug

A plug is used to plug the unused terminal cavities of a connector to prevent water intrusion. The difference between a plug and a grommet is that a grommet has a hole for the wire to pass through, while the plug does not.

Backshell

A backshell is a passive component used as an interface between the connector housing and the harness branch and to provide strain relief for wires exiting the connector.

Clips

Clips are plastic components that can be secured to a harness, often with cable ties that are then secured to mounting points on brackets along the truck chassis.

Manifold

A manifold is a component usually made out of plastic that is used to protect the harness at a junction point. It usually interfaces with corrugated tubes at each of the branches.

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1

Introduction

This chapter introduces wiring harness manufacturing and presents the main challenges within this field. The aims and purpose of the thesis are presented, along with the specific objectives that have guided the efforts. In addition, three research questions are outlined that will be answered throughout the thesis. The scope and limitations of the thesis are also presented to provide context and understanding of the decisions made throughout the work. Lastly, a declaration regarding the use of artificial intelligence tools is made.

1.1 Background

With the increase in electrification and smartification of automotive products, the need for connecting the increasing number of systems becomes more prominent (Strategic Market Research, 2022). This is reflected in the projected growth of the global wiring harness market size that was \$49.04 billion in 2021 and is predicted to reach \$74.46 billion by 2030 (Strategic Market Research, 2022). The trend of increasing connectivity entails that wiring harnesses become more complex and costly, while at the same time the labour costs to produce this minimally automated product continue to increase. This leads to successive relocation of harness manufacturing sites to economies with lower labour costs, not seldom also being further away from the manufacturing sites of the automotive product they are ultimately installed in (Nguyen et al., 2021). This attempt to reduce costs by means of relocation can increase shipping times, resulting in long lead times (Lorenz and Mayer, 2023). Ultimately, the long lead times from relocating manufacturing to low-wage countries also result in a negative cost impact when it comes to logistics costs and costs associated with product change (Lorenz and Mayer, 2023). With cost of manufacturing projected to further increase in the future due to increasing labour costs in developing countries, the need arises for an innovation in production processes that can combine the benefits of lower production costs and shorter lead times.

This thesis was conducted at Volvo TTI, the organisation that is responsible for developing and manufacturing trucks for the Volvo Trucks brand, one of the largest actors within the transportation sector. With a strong customer-centric approach, the company offers its customers countless customisation options, which lead to a large number of possible variant combinations. Whether this involves fuel tanks, suspension type or axle configurations, it directly impacts the variety of wiring harnesses, and even for electrically non-connected variants like suspension types, harness routing is often impacted due to a change in routing paths. This variety comes with several drawbacks such as high manufacturing cost and long lead times, due to manual manufacturing outside of the countries where the final truck assembly

takes place. With contribution to faster R&D cycles, product cost reduction and increase in product quality, automation of wiring harness manufacturing is directly in line with Volvo TTT's strategy focus.

Previous undertakings to improve the efficiency and level of automation (LoA) of harness manufacturing include several methods and approaches, such as using projectors to reduce the cost of change for harness layouts on routing boards (WiroBoard, 2022), using robots in collaboration with human operators to obtain the best of both worlds (Salunkhe et al., 2023), and using computer vision and machine learning algorithms to identify harness branches for automated routing and harness sorting (Malvido Fresnillo et al., 2025; Zürn et al., 2025). Yet, none of these attempts have rendered in any significant industrial implementation, which Trommnau et al. (2019) mostly contribute to the complexity and mechanical properties of wiring harnesses, leading to automation levels remaining as low as 10 % in the sector (Nguyen et al., 2021). Existing literature of the state of art also tends to automate operations by replacing humans with robots directly, as opposed to breaking down the manufacturing process to first principles. Salunkhe et al. (2023) explain that humans and robots are inherently good at different tasks, meaning that trying to adapt a manufacturing process designed to be used by humans to be used by machines is not the most optimal way of solving the problem. This entails that the manufacturing of wiring harnesses needs to be redesigned from the ground up to suit manufacturing by machines rather than humans.

1.2 Aim and Purpose

The aim of this thesis is to develop a high-level geometrical concept of an automated wiring harness manufacturing solution, with a particular focus on the overall spatial layout and the interaction between the subsystems. Furthermore, the proposed concept is evaluated with respect to its potential impacts on wiring harness manufacturing, product design, associated costs, and relevant ethical aspects.

The purpose of the thesis is twofold. First, it seeks to address the complex problem of automating wiring harness manufacturing, a process that remains predominantly manual despite increasing product complexity and growing cost pressures. Through a systematic analysis of existing manufacturing processes, stakeholder needs, and previous automation initiatives, the thesis aims to identify the key barriers to automation and to develop a novel system architecture intended to overcome these challenges. Second, the thesis aims to provide the industry with an exploration of potential solutions that could support future detailed design, development, and implementation of automated wiring harness manufacturing systems.

1.3 Objectives

The main objective is to reduce the current wiring harness manufacturing cost by 15 % by developing a solution that automates select steps of the manufacturing process. This objective to reduce the cost excludes assembly of wiring harnesses into the truck. The improvement in process efficiency is to be done through technology

development of select operations of the manufacturing process.

To demonstrate that this improvement is possible in practice, a sub-objective is to develop a CAD geometry of the final solution, that can demonstrate the most relevant parts and steps of the manufacturing process. The steps to be included will be determined throughout the project based on the gaps in the literature study and the needs of the industry and Volvo TTI.

For evaluating the cost impact of the final solution, a manufacturing and product design impact assessment needs to be completed, which will then provide data and inputs to an economic assessment that can in turn evaluate the cost impact of implementing the automated solution.

1.4 Research Questions

The thesis aims to answer, and is centred around three overarching research questions. These questions in turn are comprised of several other questions. The questions are:

- *Research Question 1:* What are the challenges associated with automating wiring harness manufacturing and how can they be overcome?
- *Research Question 2:* How could the overall architecture of a solution that automates the manufacturing, or part of the manufacturing look like and how would such a solution function?
- *Research Question 3:* What impact would full or partial automation of wiring harness manufacturing have on the overall truck and harness manufacturing process, harness product design, and on the economics of the company where it is implemented?

Research question 1 encompasses studying of existing literature, patents and other information. It also includes interviews and observations with relevant parties, outlined in section 2.2. Research question 2 will in practice translate to a product development process, with needs and requirements gathering (thus depending on the answers to RQ1), constraint setting on a system level, idea generation, concept synthesis and evaluation, with an overall design of the geometric architecture of the proposed solution being the final goal. The design process does not have the purpose to dimension every detail, but rather to present a feasible layout of a solution that can be further developed in the future.

Research question 3 aims to examine the consequences of implementing the automated solution, with the main aim being to evaluate the cost impact of automating harness manufacturing. Supporting this, an evaluation of the impact on manufacturing and product design will be conducted, after which the impact will be economically quantifiable. This includes evaluating and comparing manufacturing lead times, lead times for product changes, ethical impacts and compromises between harness design and manufacturability with automated means.

1.5 Scope and Limitations

The thesis was conducted by the two authors throughout 20 weeks during the first half of 2026, at Volvo TTI in Gothenburg. Within this time frame, the planning of the thesis was done during the first week, with the remainder of the time spent on the literature study, product development and impact assessment. In addition to this thesis report, a presentation was also produced, along with a mid-term presentation approximately half-way through the 20-week period. No explicit budget was set for the thesis or for prototyping specifically. However, an FDM 3D printer with plastic filaments was made available to the authors by the company. Thus, prototyping remained limited to plastic prototypes, and a home-made Computer Numerical Control (CNC) system that one of the authors owned and that could be used to simulate automated routing.

Due to the scale of the topic area, automation of the entire wiring harness manufacturing process will not be evaluated. The manufacturing operations to be automated will be determined collectively based on the results from the data gathering, the literature study and discussions with engineers. The remaining phases of the manufacturing will be scoped out of this thesis. Nevertheless, the proposed solution will have to take into account any preceding and succeeding operations as the intention of the authors is to propose a feasible and realistic solution. Thus, accounting for the compatibility with such scoped out operations is still included within the scope.

Any proposed solution will be limited to a high-level system geometry and will not include detailed design or specification of the machine or system components. Additionally, the development of software necessary for the functioning of such a solution has been completely scoped out, and any software necessary for demonstration of hardware function or simulation will be made as simple as possible.

The thesis will mainly look at automation of chassis harnesses (see Figure 1.1), and will not focus on cab harnesses, power cables or high-voltage cables. Power cables are thick cables used for supplying 24V power to the various systems of the truck, while high-voltage cables are used in electric trucks for the drivetrain. These cables are excluded due to the relatively low product complexity, and as they are handled in other ways and are therefore not that interesting to automate. Cab harnesses are essentially a stripped-down version of chassis harnesses. As chassis harnesses are mounted on the outside of the truck, they need to be protected from the environment with wrappings, backshells and wire seals. Cab harnesses are only installed in the truck's cab, thus do not require these protections. Thus, the scope of chassis harnesses aims to look at the most complex of the connectivity products. Additionally, the aim is to solve automation for existing wiring harness designs, and thus does not consider solutions that would require drastic changes in the wiring harnesses as products, such as producing these with additive manufacturing.

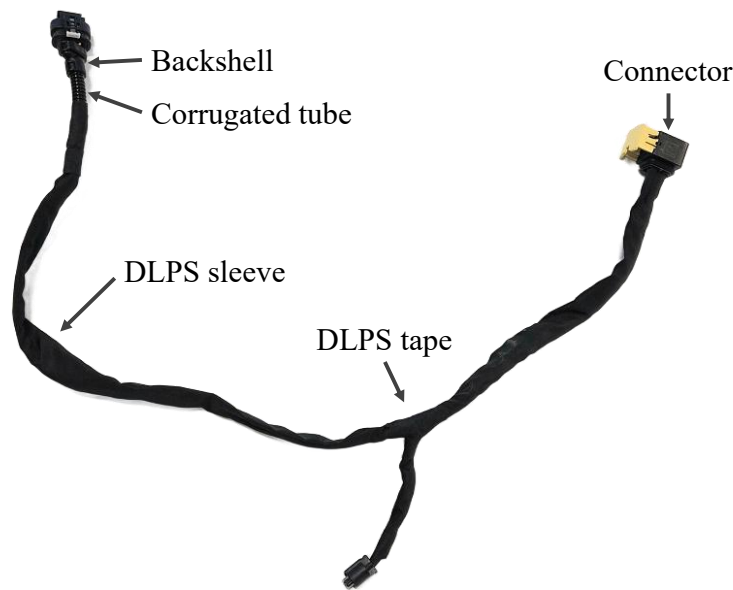


Figure 1.1: A simple chassis harness with one additional branch and labelled components

Solution capability limitations for component variety and compatibility with certain harness variants may be necessary for reducing complexity of the thesis and the proposed solution, however such solution should not inherently hinder the compatibility with any harness variants or components, as long as such necessary modifications are simple, like scaling of certain systems. Although the proposed solution is designed to be capable of handling multiple wiring harness variants, only a single harness variant family is evaluated within the scope of this thesis. The development and validation of variant management or multi-variant configuration software and algorithm is therefore excluded.

Limitations also exist when it comes to access to information. As an example, confidential and sensitive company-specific data such as precise profit margin percentages and specific product quality data could not be included in the report. In these cases, instead of company-specific data, industry-specific data or generic figures were used. In cases where such data were not available, they were roughly estimated using AI tools. In these cases, this is declared by the authors for the sake of transparency.

1.6 Declaration on the Use of Artificial Intelligence

Artificial Intelligence (AI), consisting of Large Language Models (LLMs) has been used throughout this thesis. The extent to such use has been generation of Latex-code for figures and tables, refinement of author-written text, for finding sources, and for estimating some figures in the economic assessment of the thesis. The ideas, analysis and conclusions in this thesis are the authors' own, unless the text is cited or is considered to be general knowledge. No proprietary or sensitive information has been prompted into any of the AI tools.

2

Methodology

This chapter outlines the methodology applied throughout the thesis. Following the framework of *Product Design and Development* by Ulrich et al. (2020), the study progresses from information collection through concept synthesis, screening, and impact assessment. The following sections describe each stage, including the specific methods used.

2.1 Overall Structure and Methodology

The methodology is organised into three stages, directly addressing the research questions outlined in Section 1.4. Stage 1 identifies challenges in automating wiring harness manufacturing and the needs of the stakeholders involved. Stage 2 translates these insights into a structured product development process, generating and evaluating concepts to develop a high-level system architecture. Stage 3 evaluates the proposed solution across four areas: manufacturing, product design, economic feasibility, and ethics. Figure 2.1 illustrates an overview.

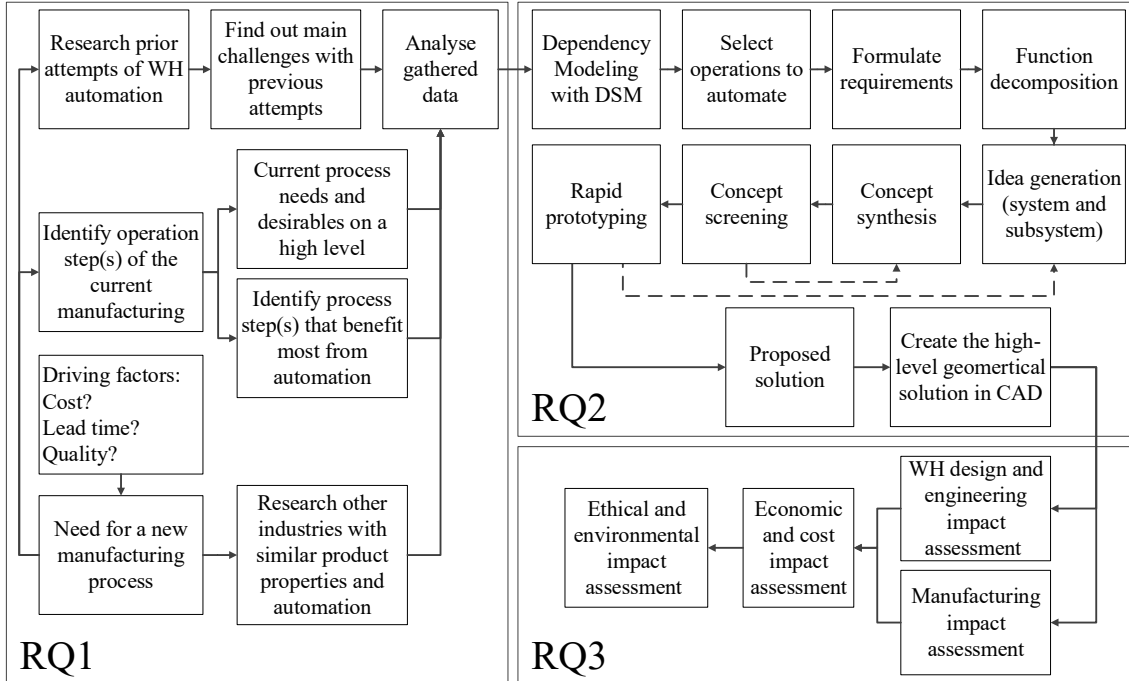


Figure 2.1: Overview of the three-stage research methodology for the development and evaluation of an automated harness manufacturing machine, where solid arrows indicate information flow and dashed arrows indicate feedback

2.2 Information Collection

The first stage establishes the foundation for the thesis by combining existing research with qualitative data collection.

2.2.1 Literature Study

A literature study was conducted primarily at the beginning of the project to establish a solid foundation for understanding the current state of wiring harness manufacturing and identifying key challenges, with additional research performed as needed throughout the project. The study covered current manufacturing methods, relevant standards, previous research and patents, as well as insights from other industries that have transitioned to automated processes.

2.2.2 Interviews and Observations

In parallel with the literature study, semi-structured interviews and, where possible, observations were conducted with relevant actors to identify their specific needs and challenges. First, interviews were conducted with wiring engineers at Volvo TTI. Key topics with this group included getting their perspectives on the current state of harness manufacturing, such as typical lead times and areas of improvement. Subsequently, employees at the electrical workshop at Volvo TTI were interviewed about topics such as which process steps are the most time-consuming and which are the most difficult to perform manually. Representatives of wiring harness suppliers were contacted for interviews to gain first-hand perspective on the challenges they face in high-volume production and assembly, but such interviews never took place. Finally, other employees at Volvo TTI were interviewed, such as cost- and quality engineers, to get a more holistic understanding of all aspects.

2.3 Establishing Scope and Requirements

The scope was further narrowed to determine which operations are most suitable to automate, while considering several perspectives. Results and recommendations from relevant literature, insights from stakeholder interviews and a process Dependency Structure Matrix (DSM) all contributed to the final scope limitation. This scope was then concentrated into a mission statement, with the requirement specification translating needs and standards into desires and requirements.

2.3.1 Scope Definition

An analysis of the current manufacturing process was conducted using a process DSM (Eppinger and Browning, 2012). The process DSM identified dependencies between operations, highlighted which could be subsequently grouped, and revealed potential efficiencies and key improvement areas. It also allowed for the reorganisation of the process into logical groups where internal dependencies are stronger than external ones. This restructuring enabled the process to be redesigned from its current state to one more suitable for automation

Based on this analysis, along with findings from the literature study, interviews, and consultations, a mission statement (Ulrich et al., 2020) was formulated to define the purpose, scope, and main objectives of the wiring harness manufacturing machine. Together, the process DSM analysis and mission statement defined the boundaries and focus areas of the project, guiding the definition of requirements.

2.3.2 Requirements Specification

Based on the defined scope and the identified stakeholder needs, a requirements specification was established. This includes both requirements (must be fulfilled) and desirables (not mandatory but fulfilment would be beneficial), and guides the subsequent generation of concepts.

2.4 Concept Synthesis

This section describes how concepts were systematically generated through functional decomposition, idea generation, and synthesis, leading to a set of complete system concepts for subsequent screening.

2.4.1 Functional Decomposition

Prior to concept generation, the total function that the wiring harness manufacturing machine shall fulfil was decomposed into a set of sub-functions using a function tree (Otto and Wood, 2001). These sub-functions describe what the machine must do to perform the necessary operations. The decomposition was based on the process DSM analysis and the scope defined in the mission statement.

2.4.2 Concept Generation and Synthesis

Idea generation was conducted in two stages. First, a top-down approach at the system level using Braindrawing (Otto and Wood, 2001) generated multiple system architecture solutions, from which one was down-selected early on by using two instances of a Pugh matrix. This was necessary early on because different system architectures require different functions, and keeping all of them would result in a far too large number of potential concept ideas.

Because this selection occurred at a crucial and consequential stage, capturing the relative strengths and weaknesses of each system architecture was deemed absolutely essential. To improve decision-making certainty while minimising time spent, the grading resolution was increased. Instead of the conventional scale of better (+), worse (-), or equal (0), architectures that were exceptionally better or worse were scored as (+2) or (-2) compared to the reference. This highlighted outliers and increased confidence in the final selection.

Second, within the down-selected system architecture, a bottom-up approach was applied at the subsystem level, starting from the lowest-level sub-functions in the function tree. Related concept ideas were subsequently grouped into nine subsystems based on emerging patterns. Each potential solution was sketched and documented

with a brief description and labels, and numbered according to the function tree to maintain traceability.

The generated subsystem ideas were then added into a morphological matrix (Ulrich et al., 2020). The nine subsystems form the rows of the matrix, with their corresponding ideas in each column. By selecting one subsystem idea from each row, complete system concepts are formed. This morphological matrix was iteratively updated, with subsystem ideas being eliminated throughout the screening process.

2.5 Concept Screening

This section describes how the generated concepts were evaluated and narrowed through a structured screening process, leading to a converged solution for further development.

2.5.1 Concept Evaluation

The combined solutions were evaluated and narrowed through a three-phase screening process consisting of an elimination matrix and weighted Pugh matrices (Ulrich, 2014). This ensured that solutions were first assessed against must-have criteria before being subjected to detailed comparison.

First, an elimination matrix was applied to quickly remove concepts that did not satisfy requirements. Each concept was assessed against a set of go/no-go criteria derived from the requirement specification. Concepts that did not meet all must-have requirements were eliminated from further consideration without detailed scoring. The reason for elimination was traced back to the combination of subsystem ideas to understand whether a specific idea or combination of ideas was the reason for elimination. The morphological matrix was updated accordingly.

The remaining subsystem ideas were then evaluated within each subsystem using weighted Pugh matrices (Ulrich et al., 2020), where subsystem ideas were compared against a reference using subsystem specific criteria derived from the requirements specification. The criteria differs depending on the subsystem, as subsystems have different tasks, functions and priorities. This identified the most promising candidates within each subsystem.

To evaluate the complete system concepts, two separate weighted Pugh matrices were conducted, each with a different reference concept. In both cases, alternatives were compared against the respective reference using the ranked desirables defined in the requirements specification. Concepts were scored using a simple scale: better than (+), same as (0), or worse than (−) the reference. This comparison highlighted relative strengths and weaknesses.

Following this, concepts were selected for rapid prototyping based on two distinct criteria:

1. **Promising concepts:** Concepts that scored consistently well across evaluation criteria were prototyped to validate their predicted performance and identify any

hidden shortcomings.

2. **Concepts requiring further information:** Concepts where theoretical evaluation was inconclusive due to lack of data, high uncertainty, or conflicting predictions were also prototyped. In these cases, prototyping served as a means of knowledge acquisition rather than validation.

This dual selection ensured that prototyping resources were directed both at confirming promising ideas, idea combinations, and at reducing uncertainty.

2.5.2 Rapid Prototyping

Following concept screening, selected subsystem ideas were developed into prototypes using rapid prototyping methodology (Ulrich, 2014). Each prototype was designed using CAD in Creo Parametric, printed with a 3D printer, and evaluated on a test rig comprising of a CNC machine, connected to a computer running a control software. The prototypes were built and tested to assess physical feasibility, gather missing data, identify unexpected issues, and validate or invalidate assumptions. This enabled fast feedback with minimal resource investment.

2.5.3 Iterative Redesign

The evaluation, including both prototyping results and concept screening, directly informed iterative redesign. Two types of iteration were conducted:

1. **Generation of new subsystem ideas:** When concept screening revealed that a specific sub-function had not been adequately solved, new subsystem ideas were generated for that subsystem only.
2. **Redesign of existing subsystem ideas:** When a subsystem idea showed partial promise but had specific flaws, it was redesigned rather than replaced entirely.

Both iteration paths fed back into concept synthesis using the morphological matrix, after which the new concept was subjected to another round of concept screening and rapid prototyping. However, concepts evaluated through rapid prototyping sometimes bypassed screening and went directly to another round of prototyping, especially for small changes. The results from these rounds of prototyping fed back into the theoretical screening methods and facilitated better decision-making when conducting the final weighted Pugh matrices. This process is illustrated in Figure 2.1, where the dashed arrows indicate the feedback from concept screening to concept synthesis, while feedback from prototype testing sometimes loops directly back to prototype design.

2.6 Impact Assessment

The impact analysis on manufacturing consists of a cause-and-effect analysis on both a micro- and a macro-level. Part of the analysis is supported by existing literature in the area. The manufacturing impact analysis will take into account the following two scenarios; impact of implementation of the proposed solution and

impact of implementation of an expanded solution resulting in near-full automation. The impact on wiring harness design and engineering will also be evaluated.

The economic impact of implementation of the proposed solution will also be evaluated for the two scenarios. This impact analysis will be grounded in a Net Present Value (NPV) analysis, that is one of the recommended methods within Volvo TTI to evaluate cost impact. Usually, the NPV formula is used to measure the net value of undertaking a project, though here cash inflows are not deemed relevant for the economic assessment. The reason is two-fold; first, cash inflows are assumed not to be impacted by automation initially, second, isolating the harness-related cash inflows from the final truck sales would not be feasible. Instead, the NPV formula will be used in a comparative sense, where the resulting value will reflect whether the implementation would produce net savings or a net loss compared to the current way of manufacturing. The proposed equation is presented in Equation 2.1.

$$NPV = \sum_{t=1}^n \frac{S_t - M_t - K_t}{(1 + r)^t} - I_0 \quad (2.1)$$

In the proposed equation, t stands for years after implementation and r for the discount rate, which is company-specific. Making up the net annual savings, S_t includes the manufacturing, tooling, and engineering savings after automation, M_t is the annual maintenance cost of the eventual solution and K_t includes any additional costs during the year, such as machine purchase costs. Finally, I_0 is the initial investment cost.

Furthermore, the rate of implementation of an eventual solution fleet can be represented with a diffusion function, similar to what Bass (2004) and Rogers (1962) propose. The implementation is expected to depict an S-curve, with implementation being slow in the start, speeding up mid-way through, and slowing down again as full adoption nears. The rate of implementation applied within this thesis can be seen in Equation 2.2.

$$N(t) = \frac{N_{max}}{1 + e^{-k(t-t_0)}} \quad (2.2)$$

In the equation above, $N(t)$ is the number of implemented solutions at year t , N_{max} is the final number of solution instances in the fleet, k is the diffusion rate which is unit-less, and t_0 is the year of fastest diffusion (here, rollout of the solutions). This equation is relevant as it will affect costs and savings dynamically, as the manufacturing is gradually automated over the years.

In addition to the application of these equations, a deeper cause-and-effect analysis will also take place from an economic standpoint. Lastly, an ethical impact assessment will similarly be conducted, where the impact on individual people, the wider stakeholder groups and the environment will also take place.

3

Literature Study

A literature study was conducted to understand the current manufacturing process, what the driving factors are to improve the current process and what progress has been made towards full automation of wiring harness manufacturing. Additionally, the TRIZ principle has been applied and areas beyond the automotive and wiring harness sector have been examined in an attempt to find interesting and relevant technologies. In practice, the literature study has been comprised of reading relevant articles and patents, interviewing stakeholders and examining harness design and manufacturing standards.

3.1 Current Manufacturing Process for Wiring Harnesses

The current wiring harness manufacturing process was reviewed to identify automation opportunities. This section covers the main process operations, the level of automation, key bottlenecks, and relevant contextual factors such as applicable standards.

3.1.1 Overview of As-Is Manufacturing

The current way of manufacturing harnesses is overwhelmingly manual. Nguyen et al. (2021) estimate that generally within the industry, up to 90% of the final harness assembly process is performed manually. These manual operations include routing the prepared wire lengths along an assembly board (see Figure 3.1), inserting the terminals into connector housings and plugging any unused cavities of housings. Other operations that are typically performed manually include adding hardware such as backshells, manifolds and corrugated tubes, adding protective sleeves or tape and positional tape and adding cable ties and clips. Operations such as cutting, stripping, and crimping wires can nowadays be performed in automated ways; however, all harness manufacturers still do not apply such technologies to all harnesses. Splicing cables is also done in a semi-automated way as the wire ends are positioned by hand while the machine executes ultrasonic crimping. However, it can be noted that even for predominantly manual operations, automated solutions are becoming more common, but often require manual placement of parts and manual removal of the modified component after the operation is finished. Thus, even such methods cannot be considered fully automated.



Figure 3.1: Wiring harness assembly board mounted along a rail. Source: Versigent PLC, used with permission

As-is manufacturing is structured in the following way: cutting, pre-assembly and final assembly (Nguyen et al., 2021). Harnesses may be produced either in a modular way or in batch, depending on the usage and variability of a harness. However, in this thesis these structures won't be considered, as they support the current manufacturing process, and changing the process from the ground-up may result in a different structure altogether.

3.1.2 Wiring Harness Manufacturing Standards

During harness manufacturing, certain standards need to be followed to ensure consistent quality and reliability. These standards include industry-wide standards such as IPC/WHMA-A-620E, and company standards by Volvo Group. These standards regulate the quality of manufactured wiring harnesses. The latter also includes company-specific schematic symbols and conventions.

For the sake of not over-constraining early on, these standards will not be considered as fix requirements, as doing so would limit the design freedom while developing an eventual solution. Instead, they will be looked at as guidelines, as much of the content have been developed over decades of trial and error within the industry, and would be wise to respect to some degree. The reason for this is that an improvement in quality or reduction in cost may warrant changes in conventions and standards.

Other ISO and IPC standards deemed relevant for the requirement setting were also examined, such as manufacturing-, quality-, and safety-related standards.

3.1.3 Wiring Harness Manufacturing Process

To understand the current method of manufacturing harnesses and identify opportunities for automation, the process was broken down into individual operations based on industrial observations. These operations were then grouped into five categories: *Setup*, *Wire Preparation*, *Wiring Operations*, *Harness Protection*, and *Finishing*, based on both the typical sequence of manual assembly and the functional similarities of the operations performed in each step. The resulting process flow, shown in Figure 3.2, provides a simplified representation of the current manufacturing procedure for harnesses.

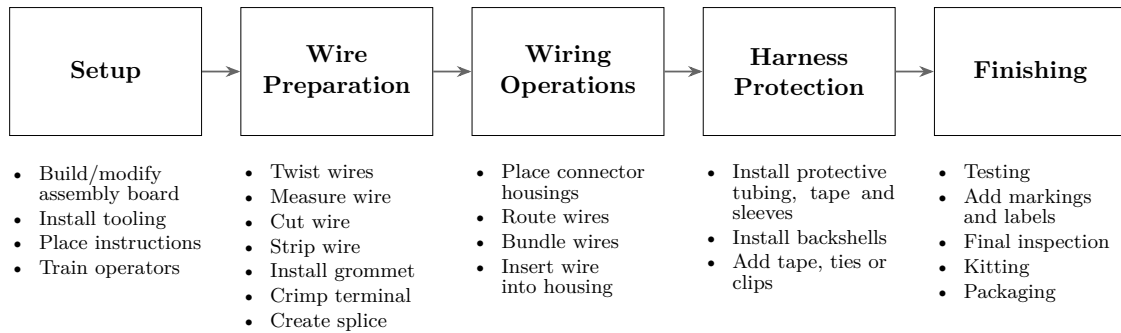


Figure 3.2: A high-level simplified overview of the current wiring harness manufacturing process, showing the main categories and their corresponding operations

The first step, *Setup*, is a one-time preparation process performed before manufacturing begins. This involves creating the assembly board based on wiring schematics and bundle drawings, ensuring that connector positions and routing paths are accurately represented. Often, several assembly boards are needed for every harness to increase manufacturing speed. A sheet is used as a base, and the printed schematic, routing forks, and connector holders are added. In some cases, tooling such as adjustable connector holders allow certain parameters, such as wire lengths, to be modified without rebuilding the entire assembly board. Once the board is configured, any necessary instructions, labels, or tool boards are placed for operator reference, and operators are trained on the process before manufacturing starts.

Wire Preparation includes all operations required to prepare individual wires for assembly. These operations include wire twisting when required, measuring, cutting, and stripping each wire to the specified length. If necessary, grommets are installed and terminals are crimped onto the wire ends. Splices are also performed when required. It is worth noting again that several of these operations, such as cutting and stripping, are commonly automated in current wiring harness manufacturing.

Wiring Operations is the assembly stage in which connector housings are added to the holders on the assembly board, prepared with plugs in the unused cavities to ensure protection against environmental factors such as moisture, see Figure 3.3. The prepared wires are routed along predefined paths, with mounting forks that are used to hold the routed wires. Electrical tape and cable ties are also used to

bundle the wires at this stage. The wires are then inserted into the corresponding cavities of the connector housings according to the wiring schematic. This step is predominantly manual due to the complexity and precision requirements of routing and termination. In instances where the harness protection consists of regular corrugated tube or DLPS sleeve, this is added prior to the termination of wires into connectors.

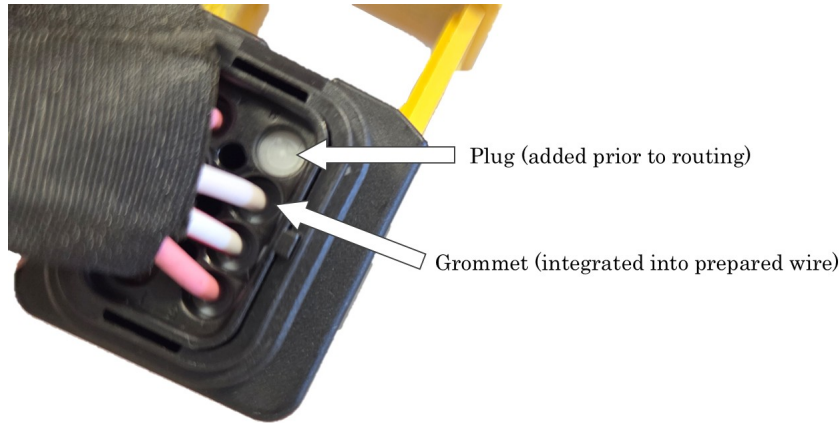


Figure 3.3: Close-up picture depicting a connector without a backshell, with its cavities filled with plugs and terminated wires with grommets

With the wires routed and terminated into connector housings, the process continues with *Harness Protection*. A terminated wire refers to a connector housing into which prepared wires have been inserted. Protective components such as corrugated tubes, dual layer protection system (DLPS) sleeves, and jackets are applied over vulnerable sections. Often, backshells are added to connectors for additional support. Supplementary tape, ties, or clamps are used to fix components. Like wiring operations, this step is performed predominantly manually today.

The final step, *Finishing*, includes all post-assembly operations required to verify and prepare the harness for delivery. Electrical testing ensures proper connectivity and function. Special boards are used to test harnesses, and in many cases, screens are used to indicate proper or improper connectivity. Coloured tape is added at certain points to indicate anchor points at assembly. Harness-level markings, labels, or tags are added for identification and traceability. A final visual inspection is conducted before the harness is kitted and packaged for shipment to the next stage of manufacturing.

3.2 Literature Review of Relevant Research

The aim of the literature review was to understand past attempts within these areas relevant to wiring harness manufacturing. Mainly, search platforms like Google Scholar were used, with search terms like "wiring harness" AND "machine", "wiring harness" AND "automation", ("wiring harness*" OR "wire harness*" OR "cable harness*") AND ("design for automation" OR "design for assembly" OR DfMA OR DfA), and "automat*" AND wiring harn* AND manufact*. Various AI tools were

also used to retrieve, summarise and understand sources, however such information was always confirmed by reading the referenced source.

The articles were loosely read and sorted into categories based on perceived relevance. 23 of these articles were kept, of which 10 were categorised as most relevant and core to the thesis, 9 were considered as possibly relevant for specific parts of the thesis, and 4 articles were considered less relevant but still interesting, as they could still be useful depending on the direction taken during the product development phase of the thesis. This categorisation also included addition of topic tags to each source, to understand the most researched topics within the field.

3.2.1 Wiring Harness Manufacturing State of the Art

Multiple articles were found that provide an overview of harnesses and their manufacturing process. These articles were useful in understanding the complexity of harnesses as products, how they are manufactured today, developments within harness manufacturing, and the driving factors for more automated processes.

Currently, almost the entire wiring harness manufacturing process is performed manually (Trommnau et al., 2019), with only wire preparation being widely automated (Nguyen et al., 2021). According to Trommnau et al. (2019), the processes of routing and adding wrappings contain the most labour-intensive operations, with these stages taking up to 50 % of the manufacturing time (Nguyen et al., 2021). The current manufacturing of wiring harnesses is often conducted in several sub-assemblies (also called modules) which are then combined on an assembly board. Still, the final assembly makes up 70 % of the total manufacturing time, and is at the lowest 10 % automated (Nguyen et al., 2021). Meanwhile, this contrasts with high automation in other manufacturing processes. For example, over 90 % of car body construction is automated (Nguyen et al., 2021). This leaves a significant hole in process development for wiring harness manufacturing compared to wider automotive manufacturing, and presents an opportunity for innovation.

According to the literature, there are several reasons why such process innovation has not taken place. Nguyen et al. (2021) points out that wires have particularly challenging characteristics for automation. Their elongated shape, ability to deform both plastically and elastically, and lack of compression strength make them difficult to manipulate with automated systems (Nguyen et al., 2021; Trommnau et al., 2019). Objects with such properties are often referred to as deformable linear objects (DLOs). Furthermore, wiring harnesses exhibit high variant variety, making traditional serial manufacturing approaches non-feasible for automation, as cases exist where the batch size has been as low as a single harness for a particular variant (Trommnau et al., 2019). In general, wiring harnesses also consist of a large number of parts (Trommnau et al., 2019), which complicates an automated solution.

In recent times, patent activity within wiring harness manufacturing has increased; however, this activity has not been translated into implementations within the industry (Nguyen et al., 2021). The lack of technical solutions capable of manipulating DLOs may also be due to the large investment costs associated with novel and com-

plex technology (Trommnau et al., 2019).

An automated harness manufacturing system therefore needs to be able to handle high product variety, low potential batch sizes, large numbers of different parts, and must be able to handle the nature of DLOs. In addition, high product quality and traceability are needed due to the increasing number of autonomous vehicles and the emphasis on safety for these (Trommnau et al., 2019). Quality and traceability are expected to improve with increased automation in wiring harness manufacturing (Lorenz and Mayer, 2023).

Finally, research has been conducted on additive manufacturing of wiring harnesses, with function-integrated and electrically conductive polymer deposition as a proposed example (Lorenz and Mayer, 2023). However, the authors dismissed the use of these types of harnesses for longer cables, and stated that more research is needed before such technologies could be implemented in the industry. Thus, such innovative approaches will not be considered, and only minimal changes to the harness product will be allowed to facilitate automation within this thesis.

3.2.2 Robotic Manipulation of Wire-Like Objects

The second identified topic included the use of robotic arms to connect housings, route wires and manipulate other DLOs. Salunkhe et al. (2023) presents theory behind the automation of harness manufacturing. Starting with the established differences between human and machine capabilities, the authors then present theory about Level of Automation (LoA) and Level of Collaboration (LoC) between human operator and robot. The authors analyse the tasks that make up the process of harness installation into cars, and break down the LoA from both a cognitive and physical perspective (LoA_C and LoA_P, respectively). They conclude that to avoid investment-heavy practical studies with regard to human-robot collaboration, correct task allocation methodology can be used. Although this article focuses on automating the installation of already manufactured harnesses into cars, the theories and models presented, especially those about LoC and the table of LoA_C and LoA_P allocation, may be useful. Such analyses are helpful when determining what humans and robots excel at, and are especially relevant when considering manufacturing automation of non-rigid products like DLOs.

Malvido Fresnillo et al. (2025) performed research involving a dual-arm robotic system for routing wire harnesses. The article includes a literature study of state of the art, the design of an integrated system that can convert a CAD-model into robotic operations, and an experimental evaluation including development on a routing platform, path planning and a cable separation algorithm, including a camera vision system. The proposed system uses two robotic arms with grippers to pick up prepared wires from a platform and then routing these wires along several pre-determined, branching paths with clamps, and inserting these ends into connectors positioned at the branch ends. Achieving an overall success rate of 55% and 73% for the two scenarios, the authors point out the cable separation process being the primary source of errors, both due to incorrect computation of grasp poses and also due to calibration issues.

Heisler et al. (2017) likewise explored using a collaborative robotic arm to route wires on an assembly board and insert wire ends into connector housings. The authors also experimented with different wire gripper designs and springy forks to retain routed wires. The authors' conclusion was that while the system benefitted from the elastic gripper and from the use of quickly manufacturable 3D-printed components, the wire loading magazine was exemplified as one area for potential improvement, the authors proposing a "multi-loader intra-logistical transport system" as a possible solution. Another issue they found was the exact positioning of the terminal on the wire end in relation to the connector housing. It was unclear whether the authors found these challenges in the axial rotation of the terminal or the lateral positioning (along the XY-plane perpendicular to the axis of insertion), but both can be considered to be challenging and need to be considered when developing an automated solution.

Although not specifically focusing on wire manipulation, Amir and Harshit (2024) focused on connector mating. They explored the practical implementation of the theory by Salunkhe et al. (2023), by evaluating the collaboration between robot and human to improve efficiency while reducing the error potential for the robot. Such collaboration reduces the need for vision systems for pre-programmed and repetitive tasks. The authors propose reducing the amount of connector families, ideally to one, to standardise the grippers that may be used in an increasingly automated installation process. Additionally, the authors propose a dual robot arm system instead of human-robot collaboration, to achieve more successful assembly, adding machine vision systems for feedback and guidance.

3.2.3 Deformable Linear Object Theory

The third identified topic is closely related to the second topic. However, the reason for differentiation is that while the second focuses more on the practical aspects for manipulating DLOs, the third topic focuses more on the theory behind DLO manipulation. The topic resulted in the findings that follow. Trommnau et al. (2020) discuss the theory behind grasping, moving and positioning DLOs, based on the object's modulus of elasticity, its length and thickness, and the forces applied to it. Additionally, they discuss the importance of correct DLO rotation, for example when aligning a terminal prior to insertion

Sanchez et al. (2018) further outline DLO theory, including the effects of plastic and elastic deformation and the benefits and drawbacks of different modelling methods such as finite element methods (FEM) and mass-spring-damper (MSD) systems. They also present previous work that has been done on linear DLOs such as cables and strings, including tying, inserting, untangling, and shaping strings and cables. While recent advances in deformation sensing based on vision systems and motion control have been made, the authors conclude that improvements in control algorithms, hardware and dexterity of the end effectors still need to be made, and that the advances made often focus on specific tasks, rather than realistic use-cases. Thus, it can be understood that manipulating an unrestrained DLO which may also attain varying positions between instances (such as loose wires) is still proving to be difficult, even with the latest technological advances.

Research by Wang et al. (2015), one of the articles referenced by Sanchez et al. (2018), used an approximate Jacobian with a virtual magnetic field to align and thread a string through a hole, both in simulation and in practice with a surgical robot. Their results are promising, but the insertion still took around 8 seconds with the lowest levels of background noise, which can not be assumed to be faster than if a human conducted the same task. The insertion time and number of misses increased with increasing noise. Rambow et al. (2012) instead investigate the use of teleoperated demonstrations to manipulate DLOs autonomously. Though they describe that with such a method, the handling of positioning inaccuracies may be difficult, which naturally arise from the properties of a DLO. The results were promising of inserting a 20 mm silicone tube through a 50 mm wide and 100 mm long gap. However, this example includes generous tolerances of 15 mm to each side from the centre of the path. For inserting a terminal into a housing for instance, requires much tighter tolerances of approximately ± 0.4 mm. Thus, a successful result by the authors is not applicable for this thesis and the control of wire ends for automating the manufacturing of wiring harnesses must incorporate appropriately tight tolerances.

3.2.4 Machine Identification of Harness Types

The fourth topic that was identified is the use of various sensors such as cameras and depth sensors to identify various features of harnesses, needed for sorting and gripping alike. Wang et al. (2023) explored research on vision systems, useful for identifying harness characteristics such as structure, error detection and detection of components, such as connectors and clamps. Detection of components is especially important for installation, but also for manufacturing for harnesses, as routing of wires involves navigating and avoiding these obstacles. The authors also highlight the lack of research on whether or not these systems are practical and reliable in a production environment. In another article on vision systems, Malvido Fresnillo et al. (2023) used a combination of edge and colour detection algorithms with machine learning to identify the position of a wire, with a detection rate of up to 91 %. While the authors describe this detection rate as impressive, it would not be sufficient in a production environment. Additionally, their system did not have the capability of running in real-time and the described detection rate required significant computation time.

The results of articles involving harness bin-sorting and picking systems are relevant for a different reason as they point to the difficulty of harness identification and handling once physical control over the harness is lost, with success rates rarely surpassing 80 % to 90 % for tasks such as grasping and sorting of harnesses (Malvido Fresnillo et al. (2023), Zürn et al. (2025)). Thus, the error rate for these systems is still unacceptably high for industrial applications. This points to a core need of integrating the process from *Wire preparation* to *Harness protection*, in a way where wires are not released before all wiring operations are completed, so control over them does not need to be regained.

3.2.5 Cost Assessments of Automation

The fifth and last topic that could be identified in the literature was various types of cost calculation. This topic holds weight as an eventual implementation of a solution in the industry is closely dependent on the cost-effectiveness of the solution. This includes all costs, such as operational costs, overhead costs, rate of productivity, but also less obvious costs such as costs associated with defects, quality issues and material waste.

Currently, due to increasing manufacturing costs, manufacturing of wiring harnesses is successively moved to lower and lower wage countries (Lorenz and Mayer, 2023). For example, countries in Eastern Europe are commonly used to produce harnesses due to relatively favourable labour costs and short transport times within Europe (Trommnau et al., 2019). However, harness manufacturing is increasingly being established in North Africa as wages in Eastern Europe continue to rise. The resulting longer transportation routes and additional interim storage lead to increasing logistical costs, longer lead times and increased transport emissions (Lorenz and Mayer, 2023).

As a result, both academia and industry are increasingly interested in comparing economic consequences of automation at different levels (Aguirre et al., 1997; Navas-Reascos et al., 2023). These articles use various formulas to compare manual, collaborative semi-automatic and near fully automatic scenarios to determine the financial viability and break-even points of these scenarios. For example, Navas-Reascos et al. (2023) used a Cost-Benefit Analysis (CBA) to determine if a collaborative production process would be viable. They present a CBA method and explain that for collaborative manufacturing to be viable, the total costs per harness for the semi-automated manufacturing process need to be lower than the total costs for the current manual manufacturing process. Equation 3.1 by Navas-Reascos et al. (2023) demonstrates this condition, with the costs of manual processing being the labour rate (L) times the cycle time (T_{M1}). For collaborative processing, the labour rate is multiplied by a new cycle time and the running costs for the machine are also added.

$$L * T_{M1} > L * T_{M2} + \alpha(T_C) \quad (3.1)$$

It is unlikely that human labour will be cut entirely, as even for “full” automation, some operators would likely be needed. Lorenz and Mayer (2023) outline that final product costs rise significantly as manufacturing automation nears 100 %, as special purpose machines are needed to complete the remaining difficult-to-automate and less frequent operations. Thus, manual labour will most likely remain, both for completing the aforementioned operations and for monitoring the automated manufacturing line, which means that the above condition would still be valid for near-full automation. Navas-Reascos et al. (2023) also found that the break-even point for collaborative investments were much sooner in high-wage countries than in low-wage countries where workforce is cheaper, while the cost of machine operation does not fluctuate significantly based on the country. This was also confirmed by Lorenz and Mayer (2023).

Aguirre et al. (1997) concludes that while automation would be economically fea-

sible for complex harness variants and large volumes, for simple harnesses and low volumes, manual labour would still be lower-cost. The main issue with such assumptions however, is that when comparing manual and automated solutions and their economic impacts, the automated solutions still consist of a harness-variant-specific assembly table. This assumption is comparable to including the costs of tooling for injection moulding when analysing the cost impact of a more flexible manufacturing method, such as additive manufacturing. Thus, the literature tends to replace the human worker with a machine in a one-to-one swap, often with a robotic arm. Naturally, this leads to unfavourable economics for small scale or one-off production, as humans are more adaptable for such scenarios. However, all possible scenarios need to be considered. In a scenario where any harness can be manufactured with an automated system without reconfiguration, tooling costs would be eliminated, with only the costs of designing that harness and any material costs remaining. This would make it possible to manufacture a large batch of identical harnesses, followed by the manufacturing of a one-off harness with no additional setup time or cost in-between. This would be comparable to how additive manufacturing can produce two completely different objects after each other. Thus, the validity of certain economic analyses depends on the character of the automated solution.

Additionally, both quality and resource utilisation are expected to improve with automation (Lorenz and Mayer, 2023). Harness quality is expected to improve as humans are inherently prone to make errors, while machines can replicate results more accurately. Resource utilisation includes both the reduction of material and component waste and also the reduction of logistics costs, as a sufficiently automated manufacturing process makes it financially viable to move manufacturing closer to the OEM and final assembly of automotive products (Navas-Reascos et al., 2023).

3.3 Review of the Industry

Additionally to the reviewed articles, a review of relevant industrial applications was also conducted. The efforts was focused on already implemented solutions, patents, and relevant solutions in other industries. The internet was also more generally searched to find concepts and prototypes developed by hobbyists. The results from this review are useful to understand what could be implemented in an eventual solution, and if certain technology could be applied in an eventual solution.

As stated earlier in this thesis, numerous solutions exist capable of automatically manufacturing prepared wire lengths, with mounted grommets and terminals. Solutions also including wire insertion into connectors, wire routing and bundling are fewer. To find such solutions, initial searches for relevant companies were conducted with search engines and patent search tools.

3.3.1 Patent Search

A patent search was conducted as part of the literature study, fulfilling several needs. First, it illustrates the recent developments in the wiring harness manufacturing industry. Nguyen et al. (2021) explains that patent activity has increased within the

industry in recent times due to the demand for automation. Second, the patent search was used to investigate the gap between patents and implemented manufacturing systems. For example, several patented manufacturing solutions, even dating back to the 1980's, have yet to be implemented. Third, the search was also useful for mapping out which companies are the most interesting and relevant to investigate further. Fourth, the patent search was also useful for investigating the concrete technical principles and ideas of automated solutions, and to avoid intruding onto existing patents with an eventual solution.

The patent search was mostly conducted with the Espacenet database tool provided by the European Patent Agency. Search terms such as “ctxt any "wiring harness machine"” and “ctxt any "harness manufactur*” were used in the initial search to get a wide range of patents. Naturally, some relevant companies were found by other means, so targeted searches were also conducted to explore the patents of these companies. For such targeted searches, search terms such as “pa any "komax holding ag" AND ti any "wiring harness"” and “pa any "fraunhofer" AND ctxt any "harness"” were used. In Table 3.1, the most interesting patents that were found are listed.

Table 3.1: Relevant patents and patent applications identified during the literature review

Patent number	Applicant	Title	Relevance to project
WO2025168824A1	Q5D TECH LIMITED	Installing a twisted pair of wires into a target structure	Twisting wires for CNC extrusion
US2025353249A1	Q5D TECH LIMITED	Wire trap and method of forming a wire trap	Secure wires to build plate with polymer deposition to form channel
US2023415410A1	Q5D TECH LIMITED	Device having a non-planar layer, apparatus for manufacturing a device, and method of manufacturing a device	Route wires in third dimension by building support structure upward
EP0241939A1	SUMITOMO WIRING SYSTEMS	Method for forming WH and apparatus for the same	WH manufacturing system
US5970609A	SUMITOMO WIRING SYSTEMS and others	Method of manufacturing WH for automobile use	Automated WH machine with no routing and IDC terminals
US6260267B1	SUMITOMO WIRING SYSTEMS and others	Manufacture of a WH	Automated WH machine with no routing and IDC terminals
JPH09320364A	SUMITOMO WIRING SYSTEMS and others	WH for automobile and its manufacture	Automated WH machine with robot arm, prebuilt tracks/guide with routing and IDC terminals
US6321445B1	SUMITOMO WIRING SYSTEMS and others	Apparatus and method of manufacturing an automobile WH having a predetermined wiring route	Routing of WH along pre-built track
JP2001023459A	SUMITOMO WIRING SYSTEMS and others	Manufacture of WH	WH manufacturing machine using IDC-terminal connectors in series
US2012152160A1	YSBRAND FLOYD R	Method and Apparatus for Producing Machine Stitched Flat WH	System for stitching wires in a flat configuration to produce a ribbon-like harness

3. Literature Study

Patent number	Applicant	Title	Relevance to project
CN209676771U	BEIJING FENGZHE TECH CO LTD	Wiring pin device of intelligent WH machine	Retractable pins for WH manufacturing machine
CN218577002U	SHENZHEN TUOZHU TECH CO LTD	Printing head assembly for 3D printer and 3D printer	Toolhead design for feeding wires
CN119795568A	SHENZHEN TUOZHU TECH CO LTD	Control method of rotation matching mechanism, medium and 3D	Feeding wires and changing wire spools
CN116214927A	SHENZHEN TUOZHU TECH CO LTD	Material selecting device for 3D printer	Method for changing spools (filament or wires)
WO2025252992A1	KOMAX HOLDING AG	Machine comprising an equipping station for equipping connector housings and a placement station having a presentation panel for producing a WH	WH manufacturing system with robot arm
DE3601116A1	FRAUNHOFER GES FORSCHUNG	Cable harness (cable loom) and method for its production	Upside-down method of WH manufacturing
Patent pending	LETRA CO., LTD	“Wiroboard.com”	Digital, reconfigurable WH routing board

Some common themes were found among the explored patents. Multiple patents used so-called Insulation-Displacement Contact (IDC) terminals, where a cut wire can be pushed into a terminal without the need of stripping or crimping the wire. Instead, the terminal has sharp, fork-shaped prongs, between which the wire is pushed into. This cuts the wire insulation and the prongs establish contact with the conductor in the wire. These terminals are commonly used in low-voltage and environmentally protected applications such as telecommunications, and in combination with ribbon cables, they greatly improve efficiency during installation (Amphenol LTW, 2025). The patents seem to use these terminal types as termination is greatly simplified also for an automated system. However, when a standardisation engineer at Volvo TTI was asked about the use of these within chassis harnesses, the engineer stated that these types of connectors haven’t been certified for heavy vehicles and chassis connectors, that experience more extreme usage than protected harnesses in passenger vehicles, where they are understood to be used.

Another theme throughout the patents is the implementation of a purpose-built wire routing track. In one patent, this semi-permanent track is proposed to be produced with a polymer and would act as a channel for the later routed wires. This would then require the same harness being produced again and again, until the track is removed and a new track needs to be made for a new harness. Thus, such a solution would add to the setup time before every new harness variant and would increase waste, both of which increase costs. In contrast, other patents completely skip the routing part and instead only handle the wire ends. In these cases, the wires are not retained in a specific shape in any way, and while this methodology would work for bare wiring harnesses for use in environmentally protected cases, it would not facilitate the automated addition of wrappings in an easy way, which would be needed for chassis harnesses.

Thus, none of the solutions in these patents fulfil all needs for a solution capable of manufacturing a chassis wiring harness in a fully automated way and without the

need for complex setup steps. Below, this is more concretely illustrated, with the analysis of existing commercial solutions.

3.3.2 Automated Solutions in Wiring Harness Manufacturing

A range of commercial automated solutions exists for different steps of the wiring harness manufacturing process. A review of existing solutions indicates that the maturity and adoption of automation vary considerably across different operations. This observation aligns with findings reported by Trommnau et al. (2019). Some stages of the process are highly standardised and well supported by automated equipment, while others remain largely manual due to the complexity and variability of harness assembly. This section reviews existing solutions and their level of automation, grouped according to the process categories introduced in Section 3.1.3. This provides context for understanding which parts of the manufacturing process are well supported by current technology and which stages remain more dependent on manual work.

Automation solutions for the *Setup* stage are limited. As described in Section 3.1.3, this stage involves preparing the assembly board prior to manufacturing. Because these tasks depend on the specific harness design and the tooling configuration, they are typically performed manually and rely on operator expertise.

Wire preparation is widely considered the most automated stage of wiring harness manufacturing (Trommnau et al., 2019). Manufacturers offer fully automatic solutions for these operations. For example, Komax offers machines such as the Alpha 520, which is designed for high-mix manufacturing with varying batch sizes and has the following key specifications (Komax Group, 2024):

- Handles wire cross-sections of 0.13 mm^2 to 6 mm^2
- Processes wire lengths of 20 mm to 12 000 mm
- Supports strip lengths up to 30 mm on both wire ends

These specifications allow the machine to process most wire types and lengths used in automotive and industrial harnesses, illustrating the high level of standardisation present in wire preparation tasks. In addition, the modular configuration allows multiple operations, such as crimping and grommet insertion, to be integrated into a single continuous process. Other manufacturers offer comparable fully automatic wire preparation solutions. The C558SSA, offered by Koder Electronics (n.d.), integrates cutting, stripping, terminal crimping, and seal insertion within a single automated platform. Automation also exists for splicing, although it is less widely implemented than other wire preparation operations. While Komax offers splicing as a processing capability on its Alpha series machines (Komax Group, 2024), a review of available machine specifications from major equipment suppliers suggests that this capability is less widely supported across the industry than basic operations such as cutting and stripping. This indicates that splicing is less standardised compared to other wire preparation operations.

Wiring operations remain considerably less automated than wire preparation (Trommnau et al., 2019). While some commercial solutions exist, they are typically specialised and less widely adopted. The Omega 850 is one of the few systems that attempts to automate parts of this process. It is designed to process individual wires and twisted pairs and insert them into pre-positioned connector housings, with the following key specifications (Komax Group, n.d.):

- Handles wire cross-sections of 0.13 mm^2 to 2.5 mm^2 (0.13 mm^2 to 0.75 mm^2 for twisted pairs)
- Processes wire lengths of 240 mm to 3000 mm
- Includes a Terminal Position Measuring System (TPMS) for optical verification of terminal alignment
- Inserts terminals into connector housings

Although the system addresses the core challenge of automated wire termination into connector housings, it is primarily designed for harnesses of limited complexity. It requires connector housings to be pre-positioned in the assembly fixture and is best suited for applications with consistent geometries and lower wiring density (Komax Group, n.d.). In high-variety production environments where harness designs change frequently, such systems become less flexible and require significant reconfiguration between batches. Additionally, this solution follows the trend of systems that cannot facilitate automated wrapping of harnesses, as outlined in Section 3.3.1.

Automation solutions for the *Harness Protection* stage are comparatively limited. Industrial robots have been used to automate selected operations in this stage. Standard 6-axis robots, such as those manufactured by companies such as KUKA, can be integrated into automated assembly cells together with vision systems, specialised grippers, and process tooling designed for handling flexible wires and connectors. Industrial projects have demonstrated the use of robotic assembly cells in wiring harness manufacturing. For example, the Next2OEM project implemented an automated wiring harness manufacturing line that combined Komax wire processing machines with industrial robots used for operations such as spiral taping, spot taping, and clip installation (Weber, 2026).

Automation solutions for the *Finishing* stage are likewise limited, as these operations often involve handling completed harnesses with varying geometries and flexible structures. However, semi-automated solutions exist for certain operations. Semi-automated test equipment is widely used to perform electrical testing before the harness leaves production. Labelling and marking operations may also be supported by semi-automated solutions, where an operator positions the harness, and a robot applies the label. Inline inspection systems may also be integrated into manufacturing lines. For example, the Next2OEM project incorporated inline vision inspection as part of its automated harness manufacturing system for quality verification (Weber, 2026).

Overall, the reviewed solutions demonstrate that the level of automation differs substantially across the stages of wiring harness manufacturing. Automation is

most mature in early process stages such as wire preparation, where standardised operations are supported by widely adopted equipment. In contrast, later stages such as wiring operations, harness protection, and finishing remain more reliant on manual or semi-automated operations.

3.3.3 Solutions in Other Industries

Apart from patent searches and exploration of existing automated solutions, a TRIZ methodology was also applied. The TRIZ methodology involves solving a specific problem within a specific domain with a solution from any other domain. The idea is that any problem has likely already been solved in another domain (Barry et al., 2010). With this in mind, the methodology was applied with an open mindset. As one example, domains where DLOs are manipulated were explored, including weaving machines within the textile industry, machines involved in spaghetti production and multi-material capable 3D printing systems. As another example, wrapping of elongated, cylindrical objects was looked into, with two examples being cigarette rolling machines and flow wrapping machines, that take a sheet on a plastic roll and transform this into a sealed tube encapsulating products such as ice cream cones.

The result from this methodology did not have any significant impact on the rest of the thesis, but some interesting principles were indeed found, such as the technology used in multi-material 3D printers that selects the plastic material. Such technology could be adapted to instead select among multiple wire rolls. The other promising principle was the flow wrapping machine. The obvious benefit of such a solution is that it could be used for wrapping harnesses even after connectors have been added, and wires could thus be terminated end to end prior to the wrapping commencing.

3.4 Interviews and Consultations with Stakeholders

Engineers within various fields were consulted for several reasons. The authors had several hypotheses of what the current challenges would be, and wanted to confirm or reject these by conducting the interviews. The authors also wanted to gain an improved understanding of the current manufacturing processes and of the supporting processes. Additionally, the answers would also support the down-selection of the scope, regarding which process operation that the product development process in Chapter 4 would focus on.

The interviews were developed to be of a short-format, with these ranging from 20 minutes to 45 minutes. This format was used as the interviews were purely conducted for information gathering purposes, rather than being user-centred. Still, some stakeholder needs would be extracted from the resulting interview answers. The number of predefined questions ranged from 4 to 10, and the nature of these depended on the role of the interviewee. The six interviews were conducted in-person in a quiet office environment, where a question was asked to the interviewee, and a discussion between the two authors and the interviewee followed, including follow-up questions. A printed interview template was used to note down the in-

interviewee's answers, no video or audio recordings were conducted. The results from the interviews are presented below, along with an introduction to each interviewed group.

3.4.1 Wiring Engineers

Wiring engineers work with designing the wiring harnesses, both in 2D and 3D. The main purpose of a 2D design is to develop a wiring schematic and bundle drawing that is used by the supplier that manufactures the harness. The main purpose of a 3D design is to route the harness along a CAD geometry of the truck to evaluate branch lengths and routing paths. They are frequently in contact with suppliers and with the truck production plant alike, and they are responsible for handling any issues with the harnesses. Below, the questions asked will be presented and a short summary of the answers are inserted below each question. The interview was conducted in its entirety with four engineers, but some questions were asked to additional engineers.

When you think of quality issues with harnesses, where can the problems most often be found? The interviewed engineers provided similar answers to this question. One hypothesis of the authors was that the current manual manufacturing process would be the source of frequent quality issues. However, the engineers did not mention anything about this, and instead described that the most problems stem from incorrect information in the wiring design, with incorrect branch lengths being a common issue. One engineer also stated that while from a product perspective, more unique branch lengths would be preferable from a product perspective, as these would fit the specific configuration of the truck more precisely, more unique branch lengths also drive up manufacturing complexity and cost.

Can you think of a harness family that has lots of variants but not very high complexity in terms of number of branches? This question was asked to find a harness family that could be used to demonstrate the function of a resulting solution. The main benefit of an automated solution would be to reduce the cost of reconfiguration between harnesses, for example a length. However, the harness needs to be sufficiently simple for an early demonstration. The answers varied somewhat, with harnesses such as *Node supply*, *VRU* and *Rear Lights* often being mentioned.

What is the typical lead time of a new wiring harness manufacturing, from design to first harness? The answers to this question varied greatly, implying that the engineer answered with the answers reflecting their own experience, as opposed to a defined standard range. The range varied between 6 to 18 weeks, mostly depending on the scale of changes to be implemented.

Can you identify any bottlenecks in the harness Design-to-Product process? The main bottlenecks identified was the configuration of tooling at the supplier, often including changes to the assembly boards. Budget negotiations for the project within which the changes are implemented was also a frequent bottleneck. Additionally, the feasibility study by the supplier could also increase the lead time, if the results from such a study are unfavourable and further actions need to be

taken. The feasibility study often includes evaluating if the changes to the assembly table that the product change request requires can be performed.

3.4.2 Electrical Workshop Technicians

Technicians that work on harness prototypes in the electrical workshop at the Volvo TTI Lundby site were consulted in hopes to get more insights into the wiring operations and to confirm the preliminary manufacturing process operations that the authors had compiled at the time. In the end, it turned out that the process to manufacture prototype harnesses varies greatly from that of manufacturing harnesses in serial production. Even if the results could not be entirely applicable, the interviews still provided insights into which parts of the harness manufacturing were challenging and difficult for a workshop technician. Three technicians were interviewed, two of them being interviewed at the same time.

What is your role and what experience do you have within the area? Mostly working on existing harnesses, rather than building ones from scratch. For example, adaption, fault tracing and modification of harnesses. Sizes vary, both when it comes to the harness and when it comes to the work order.

Is the process correct in terms of structure and order? This question was asked while the diagram with the manufacturing process steps was shown, see Figure 3.2. The preliminary order of the manufacturing process operations was created by the authors, and this question was used to get feedback on the correctness of the diagram.

What process step of the prototype construction would you skip if you could (and why)? Here, the technicians provided several answers, such as reading the instructions, re-pinning connectors, and stripping and crimping wires (while acknowledging that this is already done automatically in serial production). However, all technicians agreed that the number one operation that they would skip if they could was tapping, as it was boring and took a long time. This is useful information as taping would likely be boring in serial production too, and automating a task which the workers consider to be boring would likely make their work less monotonous as well.

In your opinion, how have the properties (complexity) of harnesses evolved over time? The expected answer to this question was about how the harnesses have changed on a higher level, for example if the amount of wires, branches and lengths have increased or decreased. Instead, all three technicians talked about component-level frustrations. While this should not be a surprising answer, as they work with these components day-to-day, this answer was thought to be contributive to the stakeholder needs.

What process step, in your opinion, is the most difficult to automate (and why)? This question was asked to gauge which steps could be interesting to automate as part of this thesis. Several operations were mentioned as answers to this question, for example final assembly into the truck and pinning connectors. The latter is especially difficult if the connector is complex with many rows and columns,

as wires can sometimes be inserted into the wrong cavity in the connector housing. Additionally, cable routing along assembly boards was mentioned as a difficult step to automate, with one technician describing it as “difficult... but not impossible”.

Can you think of any process steps that could be combined or done at the same time? This question was asked to see if there is any other room for process improvement than just automation. The hypothesis was that perhaps the expert technicians have found ways to do more with less, and perhaps this could be implemented in an automated solution. While one technician answered that measuring and cutting the wires can be done at the same time, another technician said that attaching breakout cables prior to installing the harness in testing trucks would save time later on. However, this is not something that is applicable to serial production as those harnesses don’t have breakout cables.

Do you have any personal ideas regarding ways to automate parts of the harness manufacturing? Sometimes, people that are experienced within their fields may have own ideas of doing things differently, thus it is a good idea to ask them if they do. In this particular case, however, the technicians did not have any ideas.

In addition to the six semi-structured interviews, unstructured interviews, or consultations, were conducted with the following groups. These were done on an as-needed basis and aimed to address specific questions and fill knowledge gaps.

3.4.3 Cost Engineers

Three cost engineers were consulted in total. The main reason was to retrieve information on how the cost structure looks like for the wiring harnesses that Volvo Group orders, to better understand what the costs are that can be attributed to the manual manufacturing process of harnesses. This information is needed for completing an economic impact assessment. The interviews consisted of unstructured discussions, as opposed to a list of prepared questions. The main need of cost engineers is to reduce costs, product and otherwise, by various means such as supplier selection, the modernisation of tooling at suppliers and component and material choice, among others.

3.4.4 Quality Engineers

A quality engineer was also interviewed. The interview was semi-structured with a few prepared questions and topics. The quality engineer that was interviewed had a long experience within the company and within the area, and is regularly in contact with suppliers and is also responsible for quality assurance at suppliers. The discussion was mainly about quality assurance processes, lead times and bottle necks within the current harness manufacturing process. The discussion provided insights into the way of working and how the relation between company and supplier looks like.

A quality responsible at the harness producer LinQ was also interviewed, but less formally. The main insight from this conversation was that standards specific to

harness manufacturing did not extend further than the IPC/WHMA-A-620 standard, so no specific standards on e.g. tolerances exist. Another insight was that the manufacturing operations taking the longest time is wire routing and producing the harness assembly tables. This insight was beneficial as both of these are operations that this thesis addresses, confirming that the thesis indeed addresses the most pressing areas.

3.4.5 Supplier

Discussions were also conducted with one of the suppliers of production-grade wiring harnesses. While initial communication showed significant enthusiasm for assistance and collaboration, and while an initial meeting was conducted, no concrete result materialised from this actor. This supplier supplies much of the chassis-wiring and uses increasingly more automation within their processes. For example, wire preparation (cutting, stripping, adding grommets and crimping terminals) is entirely automated.

To strengthen our knowledge when it comes to the wiring harnesses manufacturing industry and to confirm our assumptions about the manufacturing process, a field study at Quokka's LinQ prototype manufacturing site in Gothenburg was conducted. As opposed to the first supplier mentioned, LinQ manufacture low-volume wiring harnesses often for prototyping within the automotive and other transport industries. This means that their tooling is more frugal and less refined, and almost the entire process is manual. However, lead times are also much shorter, often only a few weeks, as opposed to months. This short lead time is necessary when producing prototype harnesses.

The process of manufacturing harnesses at LinQ is as follows. Once they have gotten an order and converted the raw harness design file to instructions, they prepare the assembly table by adding tape with hand-written instructions on section length, fixture placement and connectors among others. Then, they add fixtures consisting of regular screws or nails at the tape markings. When producing a harness, they use a semi-automated machine to measure and cut the wires and a similarly automated machine to strip them. Next, they add grommets and crimp terminals to each wire end and label these. This is needed to distinguish between two wires of the same colour that are terminated in the same place. The routing takes place along the prepared path with the screws or nails, and above the markings on the tape. When all the wire ends are routed to a termination point, a backshell is added. This varies from the process in serial production, where a wire end is terminated as soon as it is fully routed. This is because in serial production, the connector housings are already added to the holders prior to routing, whereas at LinQ, connector holder tooling is not used. The subsequent operations at LinQ are similar to the serial production, with wrappings and sleeving added in a manual way. Testing varies, however, with the low-volumes of prototype production not warranting the high costs of harness-specific testing stations. Thus, the field study largely confirmed our own interpretations of the process order.

The SII-Lab at Chalmers was also visited, where an observation was conducted of

their wiring harness related research and experiments and an informal, unstructured interview was made with a PhD candidate working at the lab. This discussion provided insights into ongoing research within the field from another perspective, and also provided advice for conducting the thesis.

3.5 Driving Factors for an Improved Process

The hypothesis prior to the interviews was that there could be three driving factors that would be the underlying reason for a more automated manufacturing process, these being high cost of manufacturing, long production lead times and lacking product quality.

The interviews revealed that both the cost of manufacturing and the lead times are indeed areas where potential for improvement could be possible with a higher LoA within manufacturing. However, when asked about product quality issues, the interviewed engineers could not recall any quality issues attributed to the harness suppliers. In retrospect, this result should not be surprising as the suppliers have decades of experience within harness manufacturing, and any significant product quality issues would have resulted in wider quality issues with the produced trucks. With this said, humans are still more likely to make errors, but processes and methods exist that pick up these errors before the harness is assembled into a truck.

3.5.1 Cost of Manufacturing

Information gathered from the interviews and Volvo TTI more widely reveals that the cost of manufacturing a wiring harness depends on several factors, at a high level being the hourly rate, the productivity and the manufacturing time per harness. The hourly rate can in turn vary due to factors such as LoA. Generally, a higher level of manual labour often leads to a higher hourly rate, which can be reduced with more automation. However a highly automated process with high running costs due to high complexity or requiring several operators can also lead to a high hourly rate.

At a more detailed level, harness cost is driven by several factors, such as the size and complexity of the harness, the amount of manual and non-standard operations during the manufacturing, the number of harness variants and the size of the produced batch. The last factor concerns economies of scale, the principle that a larger batch leads to lower costs per unit. The first three factors however, are all influenced by the product and process design. Additionally, there is a significant cost of product change due to reconfiguration of all affected routing boards.

In relative terms, the cost of wiring harnesses is rather high. Volvo TTI's internal figures show that wiring harnesses make up a sizeable part of the total truck cost. Breaking down the product cost, the harness manufacturing cost is near half of the total cost. Thus, harness manufacturing costs can specifically be attributed to be a significant contributor to the total cost of a truck and reducing this, for example by the means of process innovation, would lead to extensive cost savings.

From interviews with engineers at the wiring harness department, it could be con-

firmed that the two main factors that need to be considered to reduce manufacturing cost are the LoA and cost of change. In an ideal world, the LoA should be 100 % and the cost of change should be non-existent, however it is worth noting that such an outcome is improbable.

3.5.2 Lead Times and Bottlenecks

Looking at the manufacturing of a truck in broader terms, the wiring harness is dependent on the design and placement of many other truck components - both electrical and non-electrical. This is because fixtures, brackets and components along the routing path will impact the length of the harness branches, and the connector type and terminal pinout of electrical components will determine the connector type and wiring of the harness. One interviewed engineer described this relationship as the harness development and production setup being “[...] last in line with the longest lead time”.

The lead time varies greatly between Product Change Requests (PCRs), and during interviews various timestamps were mentioned. Generally, smaller changes were said to take around 6 weeks from request to implementation, while larger changes can take up to 18 weeks to implement. The lead time can further be impacted if the supplier’s feasibility study results in additional actions needed before harness manufacturing can begin.

Interviews with engineers from Volvo TTI described that often the largest factor in the lead time is the construction or modification of the assembly tables. For instance, if a branch on an existing harness needs to be lengthened, first it needs to be determined if the current routing table has sufficient space for the lengthening or if the table itself needs to be expanded. Then, the connector mounts need to be moved in accordance with the added branch length, which also includes modifying the wiring for the mount that is needed for testing the produced harnesses. Modification to other hardware such as moving or adding routing guides may also be needed. Routing instructions that are applied to the board itself are also updated. This process needs to be repeated for all assembly tables used to produce the specific harness.

Apart from the lead times associated with the feasibility study and changes to the routing tables, other bottlenecks also exist. During one of the interviews with an engineer at Volvo TTI it was brought up that the suppliers won’t start preparing for the manufacturing of an updated harness design until the budget is fully secured. While this is fully understandable from the supplier’s point of view as funding first needs to be secured, it does constitute yet another aspect that can affect the lead time to implement a PCR.

The communication itself, that is done between engineers at the wiring group, other functions and employees at the supplier is also a bottleneck, as all stakeholders need to have their needs met before the production can commence.

All in all, it can be concluded that the practical aspects of product change are the main factors impacting the lead time from product change request to implementa-

tion. Thus, an eventual solution needs to minimise the amount of tooling changes needed as a result of changes in the harness.

3.6 Analysis of Gathered Data and Recommendations for the Solution Development

This section analyses the data gathered from the literature review, interviews, and stakeholder consultations to address Research Question 1: *What are the challenges associated with automating wiring harness manufacturing, and how can they be overcome?*

3.6.1 Findings from Literature and Stakeholders

The analysis revealed five recurring challenges, summarised in Table 3.2 along with corresponding recommendations. Further insights are elaborated in the supporting evidence below.

Table 3.2: Identified challenges and recommendations for overcoming them

Challenge	Recommendations to overcome the challenge
No incentive due to offshoring	Strategic decisions need to be taken to ensure long-term economic sustainability
DLOs are inherently difficult to handle	Maintain control at all times until both ends of the wire are terminated
High-mix product variety and high cost of change	• Universal routing table and tooling that is reusable across multiple variants and operations • Standardise components used in harnesses, such as connectors and terminals, to reduce part variety and simplify assembly and inventory management
One-to-one human replacement	• Consider redesigning the workflow to optimise it for machine execution • Leverage the inherent strengths of automated systems rather than mimicking human actions • Avoid the use of vision-based systems • Avoid the use of robotic arms
Current solutions do not facilitate for holistic automation	Design for integration into larger systems without hindering the automation of adjacent operations

Reduced incentives for automation due to offshoring. The literature indicates that manufacturing is continuously relocated to lower-wage countries, reducing economic incentives for automation in high-cost regions (Lorenz and Mayer, 2023; Trommnau et al., 2019). Interviews with wiring engineers identified Level of Automation (LoA) and cost of change as key economic drivers. This suggests that automation efforts must be justified by strategic long-term planning rather than

short-term cost reductions. This suggests that automation efforts must be justified by strategic long-term planning rather than short-term cost reductions.

DLOs are inherently difficult to handle. Wires possess challenging characteristics for automation due to their deformable nature (Nguyen et al., 2021; Trommnau et al., 2019). Even advanced dual-arm robotic systems achieve only 55 % to 73 % success rates, with cable separation being the primary source of errors (Malvido Fresnillo et al., 2025). Once control over a wire is lost, grasping success rates rarely exceed 80 % to 90 % (Malvido Fresnillo et al., 2023). The literature therefore indicates that maintaining physical control of wires throughout the process is critical. Each release of the wire introduces significant error opportunities, suggesting that automation should avoid releasing wires until both ends are terminated.

High-mix product variety. Batch sizes can be as low as a single harness, making traditional automation approaches infeasible (Trommnau et al., 2019). Interviews revealed that routing table modification is one of the largest contributors to lead times, confirmed by a quality manager who identified assembly table production as a major time-consuming activity. Each design change requires modifications across multiple tables, meaning the time and cost of implementation grow with the number of variants. Traditional automation approaches are therefore economically unviable for high-mix, low-volume production. A potential strategy is the development of universal routing tables and reusable tooling across variants, combined with component standardisation to reduce reconfiguration complexity.

One-to-one human replacement. Much existing research has focused on directly replacing human labour with robotic systems while leaving the task unchanged. One study on DLO manipulation shows that terminal insertion required approximately 8 seconds even under controlled conditions (Wang et al., 2015). Vision-based systems have also proven insufficient, with non-real-time detection and success rates too low for industrial applications (Malvido Fresnillo et al., 2023). Together, these limitations suggest that directly replicating human actions with robots is unlikely to be technically viable. Instead, automation strategies should focus on redesigning workflows for machine execution by leveraging strengths such as precision, repeatability, and continuous control rather than mimicking human actions. Thus, simply swapping humans for robots and vision systems without redesigning the task is unlikely to succeed.

Current solutions do not facilitate holistic automation. A fundamental limitation of many existing automation systems is that they are designed to perform isolated operations without considering integration with preceding or subsequent manufacturing steps. Routing and wrapping together account for up to 50 % of the total manufacturing time, yet the final assembly remains at best only 10 % automated (Nguyen et al., 2021). The Omega 850, for example, can route wires and insert terminals, but it does not facilitate automated wrapping. Instead, completed harness branches are left hanging from the assembly board and must be manually removed, creating a critical discontinuity in the production flow. This highlights a broader pattern in which automation systems are developed to solve individual operations without enabling seamless integration with downstream pro-

cesses. Achieving holistic automation therefore requires a different design philosophy focused on automating critical manual operations while explicitly designing each capability for integration with adjacent systems. By planning for stepwise integration from the outset, individual automation modules could be combined into a coherent manufacturing system, directly addressing the gaps that currently keep the process dependent on manual labour.

3.6.2 Recommendations for Development

Based on the analysis presented in the previous section, several recommendations are proposed to guide the product development stage. The strategies summarised in Table 3.2 should be taken into consideration, along with the following additional guidelines.

First, complexity should be avoided where possible. Systems that rely on complex mechanisms, vision-based control, or robotic arms introduce unnecessary points of failure. Simpler solutions based on repeatable mechanical actions are more likely to be robust and cost-effective.

Second, the developed solution must be capable of handling component families currently used in production. As not all components are feasible for automation, some down-selection is needed, especially for connectors. Select connectors within the HDSCS family (Heavy Duty Sealed Connector Series) by TE, utilising 1.5 and 2.8 sized MCP terminals show potential for automated handling as the connector family largely features similar geometric features that can be used for grasping and positioning, in the form of the backshell lip. The 6 selected connectors with the backshell lip outlined are depicted in Figure 3.4. Further, the solution should not require changes in the design of the components, but it should also not become obsolete if design changes occur in the future.



Figure 3.4: Illustration of the 6 referenced connector housings with the backshell lip outlined

Third, the 10 principles outlined by Aguirre et al. (1997) should also be considered, two aspects are particularly relevant. Cable ties should be eliminated where possible, directly addressing the wrapping operations that account for a significant portion of manufacturing time. In addition, snap-fit connectors should be used to simplify connector assembly, allowing simple motion without screws or additional tools.

Fourth, both wiring operations and adding wrappings are strong contenders for automation. Together, these operations account for up to 50 % of total manufacturing time and remain largely manual (Nguyen et al., 2021). Interviews with electrical workshop technicians identified them as the most time-consuming tasks, with wire routing tooling specifically noted as a bottleneck that significantly increases lead times. Further analysis should determine whether the current manufacturing process can be restructured, ultimately informing the selection of the operation or set of operations that offer the greatest potential impact.

4

Product Development Process

This chapter includes the product development process of the thesis. The process started with analysing the existing manufacturing process, structuring the operations in a dependency-based order, which was then the basis for further down-selection of the scope. With the final scope, a mission statement was formed, reducing the ambitions to a single page. The stakeholder needs were synthesised from the interviews and findings in the literature, which, in combination with industry standards resulted in the requirements specification. The product development process continued with the idea generation phase, including methods like function trees and Braindrawing. The resulting ideas were structured into subsystems and added to a morphological matrix. Using this matrix, subsystem ideas were combined into concepts which were then evaluated in an elimination matrix. Finally, the remaining ideas were compared in several Pugh matrices in parallel with rapid prototyping and testing.

4.1 System Decomposition and Direction of Development

In this section, the existing manufacturing operations will be broken up and re-ordered in a process Dependency Structure Matrix (DSM). After some manual adjustments, the reordered operations will be modularised and a module will be selected for further development within this thesis, based on results from the process DSM, literature study and expert interviews and consultations. Finally, a mission statement will summarise the direction of development.

4.1.1 Dependency Modelling of Manufacturing Operations

To analyse the wiring harness manufacturing process more in-depth, a process DSM was created, sequenced and subsequently optimised. The process from Section 3.1.3 were initially taken and added to a process DSM. However, after all the relevant operations were added (except the operations within the “Setup” category in Figure 3.2), it became clear that the operations needed to be broken up further. As an example, the initial order of cutting the wire, stripping it, installing grommets, and then crimping a terminal onto the wire ends was seen as inaccurate, since crimping a terminal to the first free end of a roll of wire is possible, however cutting is required before the same can be done on the other end of the final wire length. Thus, the two sets of wire end operations have different dependencies, even if they are the same process. As a result of this principle, most of the wire preparation operations were broken up, distinguishing the operation between the two wire ends of a given

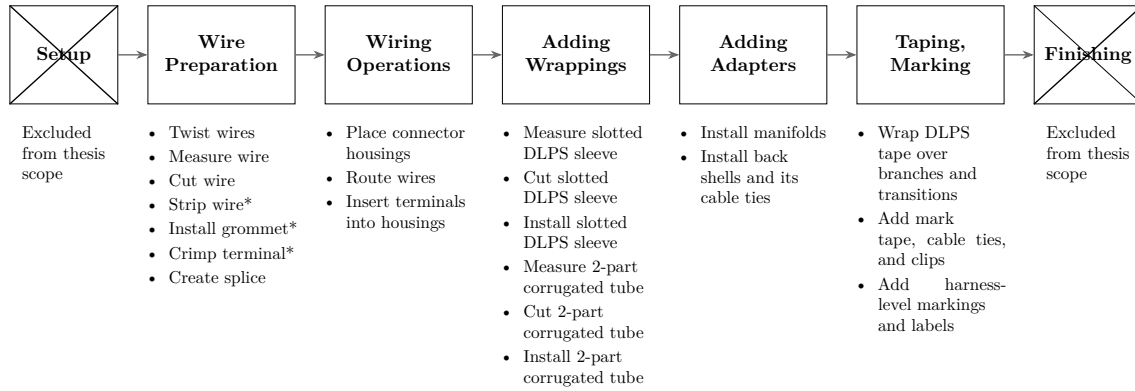
wire. In addition, the installation of corrugated tubes, DLPS sleeves, and manifolds was subdivided into measuring, cutting, and installing. Other operations were also modified; for instance, kitting and packing were broken up, and several operation names were revised to be more descriptive.

The finished process DSM consisted of 29 process operations, with dependencies arranged into a lower triangular form, meaning that an “X” is placed out in a cell if the operation in the row has a dependency on the operation in the column, as can be seen in Appendix A. The process DSM was then exported as a CSV file and uploaded to a DSM solving web tool (<https://dsmwebtool.com>). The tool was used to rearrange the operations based on the dependencies to identify elements that do not depend on other elements in the matrix, moving these to the left of the remaining operations. A sequencing and triangularisation algorithm was used to rearrange the remaining operations so that the operations’ dependencies move closer to the diagonal, resulting in groups of operations that depend more on each other than on external operations. This grouping was done manually in the modified matrix created by the DSM Web Tool, based on the operation category, see Appendix A. Some operations within the same category are dispersed because the DSM Web Tool only optimises moving dependencies closer to the diagonal and does not take operation categories into account. For example, installing manifolds and back shells sequentially makes practical sense, but the DSM Web Tool does not consider this and therefore arranged them differently.

Most of these “out-of-place” operations could be moved manually with no resulting backwards dependencies. Within wiring operations, prepared wires must be routed before any wrapping operations, such as adding corrugated tubes or DLPS sleeves, can be conducted. Meanwhile, inserting terminals into connector housings must normally take place after wrappings are complete, as the tubes and sleeves are much smaller in diameter than the housings at the branch ends. Thus, there are a string of dependencies between operations in several categories. In practical terms, automating harness manufacturing is disadvantageous if routed wire ends are released before reaching their final positions, i.e., the housing cavities. Then, control of the correct wire end has to be regained after the wrapping has been done. This task is relatively simple for a human to do, requiring only basic judgement and improvisation (Salunkhe et al., 2023), but requires advanced vision and control systems for a machine to do so.

As a result of this, conventional corrugated tubes and DLPS sleeves are not optimal for automation. Instead, slotted corrugated tubes and DLPS tape or slotted DLPS hose could be used. With this change, installation of wire terminals into connector housings can be done before any wrappings are added. This optimisation and the final process DSM can be seen in Figure A.4 in Appendix A. Note that doing this, the manufacturing operations are in an order where categorisation into subsystems can be done not just based on dependencies but also based on practicality.

Five categories excluding testing, kitting and packaging were defined consisting of: *Wire preparation* (taking rolls of wires and transforming them into prepared lengths with terminals and grommets), *Wiring operations* (taking the individual wires, routing these along a path and adding connectors), *Adding wrappings* (such as DLPS sleeves, tape and corrugated hose to protect the wires), *Adding adapters* (plastic parts such as backshells, manifolds and adapters between different hose sizes), and *Taping, marking* (taping together components, adding connector labels and positional markings, adding cable ties and clips). Note that the updated categories of operations in Figure 4.1 differ from the previously presented preliminary categories from Figure 3.2, as the operations within *Harness Protection* have been broken up. This way, the categories become more practical for automation, as handling of long, flexible components such as sleeves and tubes differ from handling small, rigid ones such as backshells and manifolds.



*Separate operations for wire end 1 and 2

Figure 4.1: Final selection of scope to automate

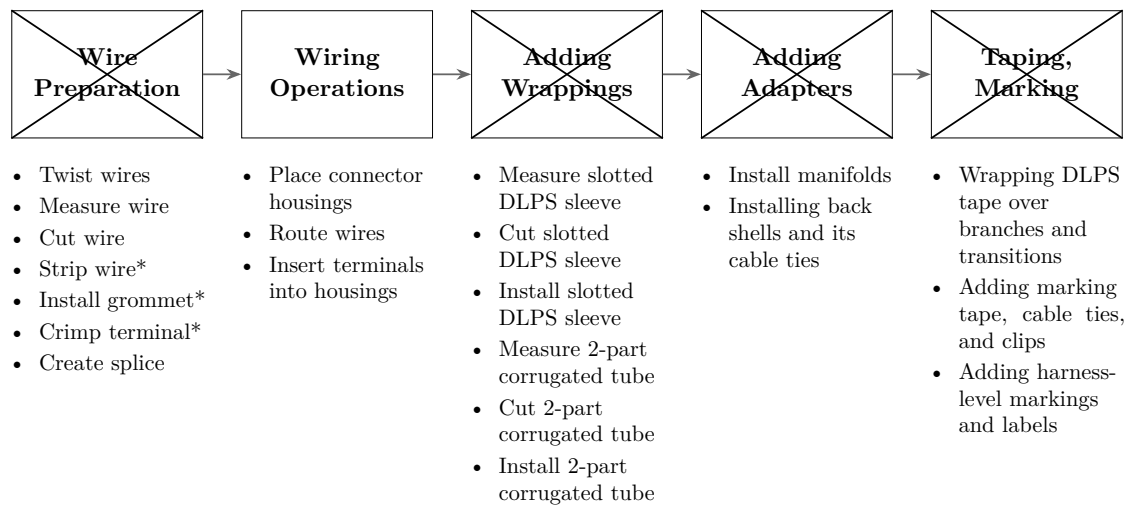
4.1.2 Selecting Operations to Automate

As attempting to automate the entire harness manufacturing process would not be feasible within the scope of this thesis, selection of a manufacturing phase comprised of a group of operations needs to be made. The resulting manufacturing phases obtained from the process DSM can be used for guiding this selection, along with results from the literature study and qualitative information gathering.

Wire Preparation has already been automated, and several fully automated solutions exist in the industry, as discussed in Section 3.3.2. In contrast, operations such as *Adding Wrappings*, *Adding Adapters*, and *Taping and Marking* remain largely manual. However, many of these operations depend on tasks performed during *Wiring Operations*, as the branches of the harness need to be bundled with sufficient clearance between branches. Automating this stage first may therefore create more favourable conditions for automating the remaining operations at a later stage. This makes up the first argument for automating *Wiring Operations*.

In addition to the method- and logic-driven selection based on the results from the process DSM, the literature study showed that while some fully automated wiring harness manufacturing systems do exist, such as the Komax Omega 850 described in Section 3.3.2, no solutions exist that can create harnesses while preparing these for later operations, like adding wrappings and other passives, in the same process. Academic research also revealed that while many examples exist of using robotic arms to route wires, create knots, thread wires, and connect connectors, none of these solutions have been adapted to industrial needs and are often performing a specific task. Qualitative methods such as interviews with engineers from wiring harness design, quality and cost and discussions with suppliers that manufacture the wiring harnesses, reveal that wire routing, and the associated activities such as installation of tooling, budget negotiations, feasibility studies, and other preparations, is the part of the process where the most bottlenecks exist.

While many sources revealed that wrapping and taping the harness is also a time-consuming part of the process, activities associated with routing the wires bring the most challenges. Thus, the activities within *Wiring Operations* were selected for automation. See Figure 4.2 for the final selection.



*Separate operations for wire end 1 and 2

Figure 4.2: Final selection of operations to automate

4.1.3 Mission Statement

With *Wiring Operations* selected as the process to develop, a mission statement was created to ensure alignment with the thesis objectives. Table 4.1 presents the resulting mission statement, which defines the purpose, scope, and main objectives of the automated solution.

Table 4.1: Mission statement

Element	Description
Product	• Solution for automating wiring harness manufacturing • The solution should produce a bundled harness for signal wires with branches and mounted connectors from fully prepared wire lengths
Benefit proposition	• Reduce lead times for harness design changes • Save costs within manufacturing • Reduce manual labour during manufacturing • Progress toward fully automated wiring harness manufacturing
Key Business Goals	• Reduce the current wiring harness manufacturing cost by 15 %
Primary Market	• Use of solution within Volvo Group
Secondary Markets	• Use of solution with other heavy vehicles (buses, construction) • Use of solution within transportation vehicles in general • Use within wider automotive like passenger cars • Use within aerospace markets
Assumptions	• Assuming that tools exist for individual wire preparation and that the order of wires prepared can be fully controlled • Needs to make possible the wrapping of the harness without manual repositioning • X2ML files are automatically converted into machine instructions (e.g. G-CODE)
Constraints	• Thesis is conducted between January 19th and June 8th, 2026 • Result is limited to a high-level CAD model and impact assessments • Prototyping will be limited and no budget is set
Stakeholders	• Volvo TTI • Tier 1 Wiring Harness Suppliers • Research community

4.2 Needs and Requirements for an Eventual Solution

This section will analyse and present the stakeholder needs gathered from the expert interviews and consultations. Further, the gathered needs will be combined with findings from the literature study, relevant standards and further scope refinement, to form the requirement specification that will be the backbone of the solution development process.

4.2.1 Stakeholder Needs

Gathered data from the interviews and consultations are compiled and analysed to obtain the needs of the interviewed stakeholders. First, the answers from the interviews were summarised in one sentence, see column one in Table 4.2. These answers were then analysed and the underlying reasons for the answers were added to the second column. These reasons - which are tied to specific problems - were then further analysed and the converted into the needs that - if fulfilled - can help solve these problems in a new manufacturing solution. These needs can be seen in the third column.

Table 4.2: Table of needs analysis

Answer in interview	Reason(s) for answer	Core needs
Wiring engineer states that most quality issues are due to incorrect harness branch lengths and marking tape positions (caused by the wiring engineer)	• No tools exist where correct branch lengths and marking positions can be simulated. • Engineers are not always informed about the problem, partly due to assembly operators not communicating these, and partly due to engineers being distant from the assembly line. • Engineers receive feedback late in the process	• Develop appropriate simulation software • Wiring engineers should be more involved in and be closer to the wiring harness manufacturing • Quality of the current production process is already high, this quality needs to be retained or ideally improved with an eventual solution
Wiring engineer states that lead times for product change requests (PCRs) are too long, even for minor product modifications	New tooling needs to be ordered and installed on assembly tables, leading to the below: • Feasibility study has a long lead time • Budget negotiations take a long time • Instructions need to be updated and workers need to be trained	• Solution should minimise the need for physical modifications of assembly tables between harness variants • PCR changes should minimise the need of updating manufacturing instructions and re-training workers

Answer in interview	Reason(s) for answer	Core needs
Branch lengths can not be perfectly adapted to a truck configuration	Adding more intermittent branch lengths drives up the manufacturing cost due to product complexity, as manufacturing tooling needs to be added	Solution should minimise the need for physical modifications of assembly tables between harness variants, reducing the need for new tooling
Electrical workshop technicians would like to reduce operations such as harness wrapping	Tasks like harness wrapping are monotonous and time-consuming	System developers should aim to prioritise automation of monotonous, time-consuming tasks

The second row in Table 4.2 can be used as an example. Long lead times between design changes and implementation were found to be because of lengthy feasibility studies (often analysing the possibility of changes to assembly boards), budget negotiations often involving the former and the actual changes to the assembly boards and any re-training of workers. The extent of these varies for every PCR. Thus, the need from this would be to minimise the need for changes to the assembly tooling, which would minimise the need for a feasibility study and in turn minimise the need for budget negotiations.

Some underlying problems, however, could not solely be addressed by a novel manufacturing system. An example is the second column in the first row, where one reason to why harness branch lengths and tape markings might be wrong was found to be that the engineers are not always informed about such problems. This can not be solely fulfilled by a novel solution, and would also require a change in the working methodology, but a solution that reduces the degrees of separation between the wiring engineer and the manufacturing process would likely result in more awareness about the product.

The resulting stakeholder needs from the needs analysis and from the standards were generalised and consolidated into Table 4.3, where the generalised needs are also attributed to the stakeholders that have that need. As an example of this generalisation, the stakeholder need “Solution should minimise the need for physical modifications of assembly tables between harness variants, reducing the need for new tooling” became the more generalised need “Reduce one-time setup costs”. As we can see, many of the needs of the wiring harness manufacturer and the Original Equipment Manufacturer (OEM, in this case Volvo Group) are equivalent to each other.

Table 4.3: Structured stakeholder needs, including needs from interviews and operational needs

Need	Stakeholder(s)
Safe operation of solution	WH manufacturing workers, technicians
Solution should not compromise the working environment and safety of workers	WH manufacturing workers, technicians
Reduction of monotonous, time-consuming tasks such as harness wrapping	WH manufacturing workers, technicians
Reduce one-time setup costs	WH manufacturer, OEM
Reduce operational costs	WH manufacturer, OEM
Improve production efficiency and speed	WH manufacturer
Retain or improve product quality	WH manufacturer, OEM
Retain or improve production quality	WH manufacturer
Integrate solution into existing production and environment	WH manufacturer
Make possible to produce desired harness variants	OEM
Reduce lead times for PCRs and new harness variants	OEM

The above needs are one of the sources of requirements in the requirement specification.

4.2.2 Requirement Specification

The requirement specification lists all the requirements and desires that need to be fulfilled in an eventual novel solution. The requirements are a composition of the stakeholder needs, internal and industry standards, documented needs from the literature study and the authors' own objectives. A condensed version of this specification can be seen in Table 4.4, while the complete specification can be found in Appendix B. The requirements and desires are listed below, numbered according to the category. Values noted as a Y or N are boolean values, either "Yes" (Y) or "No" (N). Requirements and desires (R/D) are distinguished between, with desires not requiring fulfilment for a concept to be categorised as satisfactory, being prioritised from 1 (least important) to 5 (most important).

Table 4.4: Condensed version of the Requirement Specification

No.	Requirement	Value	R/D
1.1	The solution shall manufacture a harness for signal wires with branches and mounted connectors from fully prepared wire lengths	Y	R
1.2	The solution shall manufacture wiring harnesses according to a compatible harness design defined in the X2ML file	Y	R
1.3	The solution should not require any human intervention or collaboration during manufacturing	Y	D5
1.4	Solution needs to be able to be reconfigured to manufacture a different harness with no manual effort	Y	D3
1.5	Make possible to add passives such as corrugated tubes and sleeves without manually moving the WH	Y	D4
2.1	Harness manufacturing time compared to current manufacturing time	$\geq 85\%$	D5
2.2	10-year manufacturing cost compared to current manufacturing cost	$\geq 85\%$	D5
2.3	The solution should provide a precision with respect to the tolerances needed for various operations resulting in a failure rate below the limit in 2.4	Y	R
2.4	The fraction of non conforming harnesses should be below specified limit	$RPN < 265$	R
3.1	The solution shall handle wires with certain cross-sectional areas	0.75 mm^2 to 2.5 mm^2	R
3.2	Maximum possible diameter of prepared wire	5.9 mm	R
3.3	Minimum possible diameter of prepared wire	0.6 mm	R
3.4	Maximum possible length of stiff end of prepared wire (terminal + grommet)	32.8 mm	R
3.5	Number of wire colours	11	D4
3.6	The solution should be able to route and handle long wires	up to 7000 mm	D2
3.7	The solution should be able to handle the harness with the maximum number of connectors	122 connectors at once	D2
3.8	The solution should be able to route harnesses with the specified diameter	$3\text{ mm} < X < 50\text{ mm}$	R
3.9	Terminal types	MCP 1.5 & 2.8	R
3.10	The solution should be able to handle the harness with the maximum number of connectors	6 referenced connectors	R
4.1	Safety perimeters should be established, marked and if needed the solution should be enclosed	Y	R
4.2	Solution should electrically disconnect moving systems at the end of cycle; should require manual action for reconnection of electrical supply	Y	R

Table 4.4: Condensed version of the Requirement Specification

No.	Requirement	Value	R/D
4.3	Solution should provide sufficient safety precautions such as markings, sensors, lights and guardrails showing reach in compliance with internal standards	Y	R
4.4	Solution shall provide operators with the ability to safely pause or stop operation at any time during the cycle	Y	R
5.1	Compliance with the internal standard 515-0002	Y	D3
5.2	Compliance with the trade standard IPC/WHMA-A-620	Y	R
5.3	Product quality should be at a minimum at the level of the current production methods	Y	R
5.4	Productivity and uptime should be at a minimum at the level of the current production methods	Y	R
6.1	The solution geometry shall be designed for easy integration with prior and subsequent production systems	Y	D5
7.1	The solution shall achieve wire utilisation equal to or better than the current manual manufacturing process	Y	D2
7.2	The solution shall be designed for repairability, with modular components	Y	D3
7.3	Minimise the use of custom-manufactured parts; prioritise off-the-shelf components where possible	Y	D1
8.1	Ability to operate within nominal working temperature for human workers	20 °C to 26 °C	R
8.2	Ability to operate within nominal working humidity for human workers	30 % to 70 %	R
8.3	Limit generated temperature	Depends on surface material and exposure time	D1
8.4	Limit generated sound to acceptable levels for prolonged human exposure	< 85 dB, including other sources in the facility	R

The first category of requirements are the *Functional Requirements* (1.1-1.5). These requirements and desires fulfil the core needs of a new manufacturing system, and are a combination of the mission statement, needs from the stakeholders, and requirements resulting from the literature study, that are considered to be necessary for an automated solution. The requirements 1.1 and 1.2 specify that it shall manufacture a bundled harness for signal wires with branches and mounted connectors from fully prepared wire lengths, and that the solution should produce harnesses according to X2ML files, respectively. The former specifies which operations the solution should be limited to while the latter includes both that the solution should make possible to produce any harness from a digital file and that this should be made possible with currently used wiring harness files, to ensure compatibility with the current design-to-manufacturing workflow. Requirements 1.3, 1.4 and 1.5 that are classified as desires, and aim to reduce the amount of manual labour and special

harness-specific tooling, which are the main reasons for the current high manufacturing costs. These desires are a combination of analysis of stakeholder needs and learnings from the literature study.

The second category includes the *Performance Requirements* (2.1-2.4). These include two desires, 2.1 and 2.2, which embody the expectations that an automated solution is expected to provide. These represent the expected savings when it comes to manufacturing time and cost which are both set at 85 % of current, according to the overall system goal stated in Section 1.3. Requirements 2.3 and 2.4 control are responsible for the precision of an eventual solution. For requirement 2.3, no existing set tolerances could be found. Thus, the requirement instead specifies that the tolerances should be small enough to ensure that the solution performs below the set error rate. The necessary tolerances may also vary between different subsystems and different solutions. Various ISO-standards and Volvo Group's Supplier Partner Quality Assurance Manual (SPQAM) were instead referenced. Requirement 2.4 sets the permissible error rate to be below the current manufacturing method's RPM in the Process Failure Mode and Effects Analysis (PFMEA) that was conducted involving the relevant operational steps. This PFMEA can be seen in Appendix C.

Due to the amount of variables in a wiring harness, a specific *Harness Characteristics* (3.1-3.10) requirement category was warranted as the third category. Note here that while fulfilling all requirements and desires in this category would be needed to be able to produce all harnesses within the initial scope, an additional re-definition of the scope took place here. While the harness that has the thought-to-be most number of connectors of 122, this was set as a desire as such numbers could easily change. The eventual solution could likely be expanded to handle those numbers of connectors later on. Compatibility with only 6 specific connectors are required to fulfil the requirements, as these 6 connectors had similar features that made them possible to use the same interface. For compatibility with other connectors within the same family and other families, changes in connector design are likely needed. This entails that only MCP terminals of the sizes 1.5 and 2.8 are required for the first version of the solution, as the 6 specified connectors only accept these terminals.

In addition, compatibility with twisted wires was not included in the specification to reduce the complexity of the solution. Twisted wires will be needed to be handled in a future solution to handle CAN-cables. Requirements and desires regarding various permissible harness dimensions were also set, where the compatible wire gauge sizes include all signal wires, and where the maximal and minimal diameter of the prepared wire is the largest diameter of the thickest possible wire and the smallest diameter of the smallest wire, respectively. On a prepared wire, this happens to be the outside diameter of the largest possible grommet and the diameter of the thinnest available signal wire, respectively.

These requirements, along with the requirement for accepting the longest possible stiff wire end (from the end of the terminal to the end of the grommet), were defined so that any transport conduits or tooling would be designed in a way where wires with these extreme measurements could be handled. The two extreme values for the harness diameter set requirements on the routing media, that needs to accommodate

both the thinnest possible harness (a harness comprised of a single 0.25 mm^2 wire, measuring 3 mm in diameter) and the thickest harness, which was specified as 50 mm by wiring engineers. By contrast, the maximum length of harness that should be able to be produced was only set as a desire, partly as this number is a rough estimation and is flexible, and partly that if only shorter harnesses can be produced, smaller, modular harnesses could replace a larger, single harness.

Even though an eventual solution would increase automation, human workers and technicians would likely be needed for working with, or at the least monitor, the automated manufacturing. Thus, the safety of these people needs to be ensured in relation to an eventual solution. Four *Safety Requirements* (4.1-4.4) were defined within the fourth requirement category. Some internal standards were found outlining the requirements for manufacturing systems within the company, with ISO-standards complementing these. Although these requirements are concrete, involving safety measures such as guardrails and electrical safety functions, the resulting solution within the scope of this thesis is not expected to be able to fulfil these requirements, as it is not expected to be sufficiently developed. Instead, these requirements serve to inhibit any inherent safety risks in an eventual solution, and will need to be fulfilled in a finalised manufacturing system.

The fifth category includes the *Quality Requirements* (5.1-5.4), which aim to control both the production system quality and the quality of produced harnesses. Any eventual needs to comply with the Wiring Harness Manufacturers Association's (WHMA) IPC/WHMA-A-620 standard that specifies compliant product quality for wiring harnesses. An internal wiring harness standard should also be followed if possible, however automation may or may not be compliant with this and may even require changes to this standard. Product and production quality are set as two separate requirements, and come from the stakeholder needs. These are relative to the current manufacturing method, and the requirements state that the product and production quality should be equal to or better than the current product and production quality.

The sixth category, *Integration Requirements* (6.1) includes one desire, that specifies that an eventual solution needs to be able to be integrated with existing systems. Some modifications to existing systems may however be needed, which is the reason for setting it as a desire instead of a requirement.

The seventh category includes the *Sustainability and Repairability Requirements* (7.1-7.3). Desire 7.1 aims to reduce material waste compared to the current manufacturing method, whereas 7.2 aims to have a high level of repairability with the use of modular components. Desire 7.3 specifies that these components and parts should be off-the-shelf parts to as large degree as possible.

Environmental Requirements (8.1-8.4) differ from *Sustainability and Repairability Requirements*, as the latter regards the wider impact of the product, while the former is confined to the immediate area where the solution is operated. Both requirements regarding the environment that the solution should operate in and how the solution affects the environment are included. Requirements 8.1 and 8.2 specify the operating

temperature and humidity, respectively. No exact standard values could be found for these requirements, however the limiting factor is assumed to be the human workers. Some standards provide guidelines for what temperature and humidity ranges would be appropriate for human workers, the included values thus represent these ranges. Naturally, if the solution generates a temperature or humidity higher or lower than the specified ranges, the solution should tolerate those. Should the solution generate temperature and create a hot surface, desire 8.3 should limit this according to the referenced ISO standard. Acceptable temperature depends on the surface material and exposure time, however other measures such as covering that surface twice or introducing any other barrier could also be done, which is the reason for the low priority of the desire. 8.4 limits the level of any generated sound according to the referenced standard by the Swedish Work Environment Authority (AV).

Overall, these requirements include stakeholder needs, standards-derived requirements and further scope limitation when it comes to the harness design that the solution should be able to produce. The next step in the product development process is to break down the current operations of the defined scope to facilitate idea generation and concept synthesis.

4.3 Functional Decomposition

To support idea generation, the main function of the harness manufacturing solution was broken down into smaller, more manageable sub-functions using a function tree. This decomposition resulted in four second-level functions, as shown in Figure 4.3.

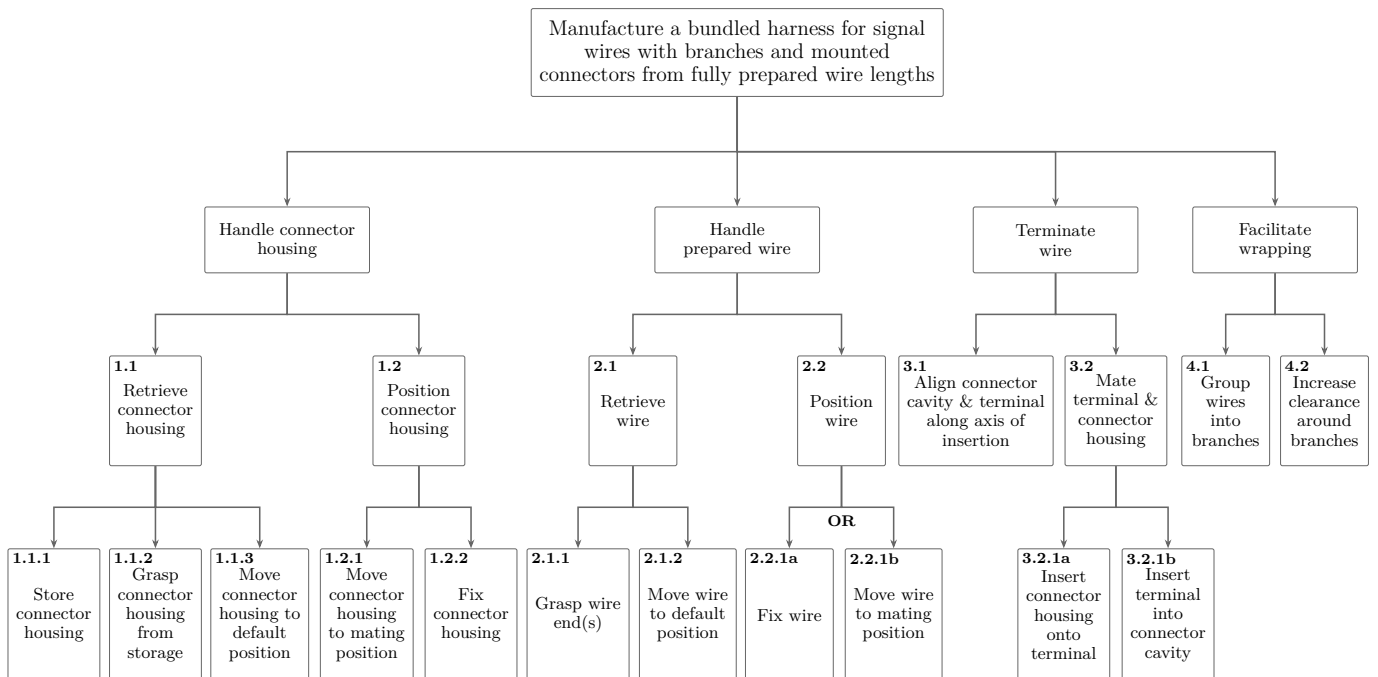


Figure 4.3: Function tree diagram showing hierarchical decomposition

The first two functions focus on preparing and positioning the physical components, connector housings and prepared wires before termination. The third function, terminate wire, represents the operation step where the wire terminal is mated with the connector housing. The fourth function handles the preparation of the harness for wrapping, which involves grouping wires and ensuring sufficient clearance around branches. Each of these functions is further decomposed into more detailed sub-functions, with the numbering (e.g., 1.1, 1.1.1, 2.1) indicating parent-child relationships and enabling traceability between generated ideas. The functions were defined purposefully at a level that avoids constraining potential solutions, leaving room for creative and varied approaches in the subsequent idea generation phase.

For instance, handling a connector housing requires retrieving it (1.1) and positioning it (1.2), with each of these broken down into specific tasks such as grasping, moving, and fixing. The “Position wire” function (2.2) includes an *OR*-relationship (2.2.1a and 2.2.1b), indicating that at least one of the wire or the connector needs to move for mating to take place. When the wire is fixed in a static position (2.2.1a), the connector housing must be the part moving, thus being pushed onto the terminal (3.2.1a). In contrast, when the wire is moved to the mating position (2.2.1b), both options from function 3.2, pushing the connector onto the terminal (3.2.1a) and inserting the terminal into the connector cavity (3.2.1b) can be used, individually or together. In other words, 2.2.1a can only be paired with 3.2.1a, while 2.2.1b allows for solutions where either 3.2.1a or 3.2.1b occurs alone, or both occur simultaneously.

An important detail to note here is that alignment of connector cavity and terminal along the axis of insertion (3.1) is necessary for the selected HDSCS connector family, as the corresponding MCP terminals are rotationally asymmetric, so-called tab and receptacle terminals. Thus, the terminals first need to be rotationally aligned prior to insertion into the housing, or insertion will not be possible at all. This asymmetry can be seen in Figure 4.4.

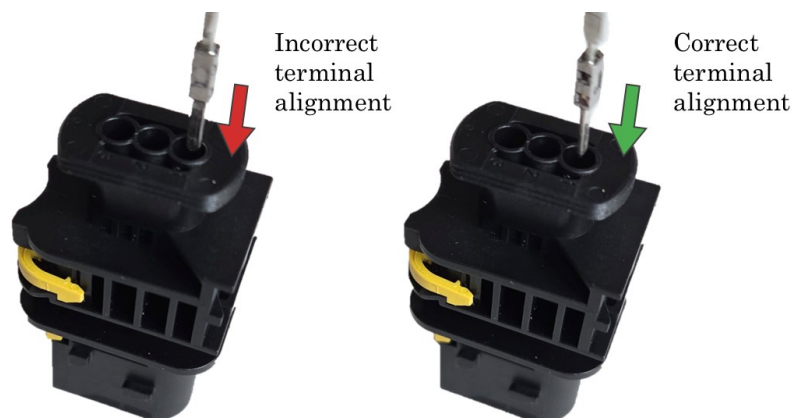


Figure 4.4: Incorrect alignment of the terminal and correct alignment of the terminal in relation to connector housing cavity

The function tree reveals which sub-functions cannot be combined, which can be combined freely, and where relationships exist between functions. The following section presents the idea generation process based on this decomposition.

4.4 Concept Synthesis

Building on the function tree, this section presents the generation of potential ideas for each sub-function, first at a system level and then in detail. The first stage followed a top-down approach to comprehend the overall architecture without going into detail too early, allowing for an understanding of how the system could be configured. With multiple unique system architectures generated, a screening was conducted to reduce the number of concepts. After one system architecture remained, detailed idea generation began at the lowest-level sub-functions in the function tree, following a bottom-up approach.

4.4.1 System-Level Idea Generation

To avoid limiting ideas to a single system architecture, two authors each performed brain drawing on one third of an A3 paper over 10 minutes. The papers were then exchanged, and each author continued brain drawing on the other's idea for an additional 5 minutes. This process was repeated two more times until all three thirds of each paper were filled with system-level idea sketches (see Figure 4.5). To maintain traceability, the corresponding numbering from the function tree was then mapped onto each idea.

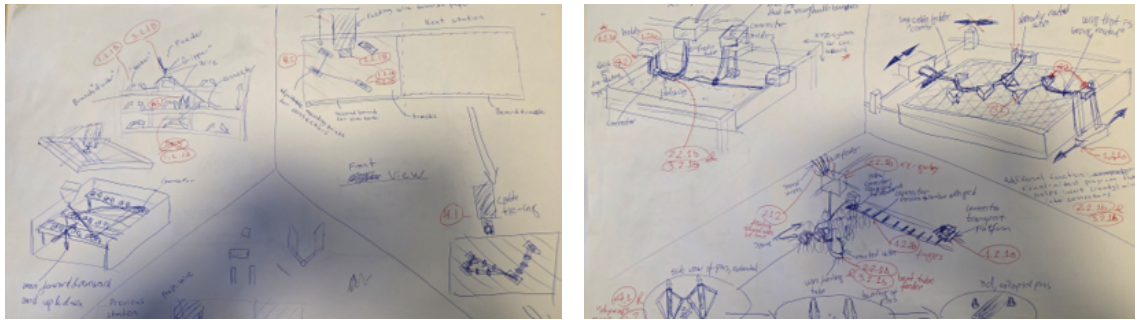


Figure 4.5: Pictures of some of the initial system architecture sketches

This resulted in a total of eight unique system architectures, summarised in Table 4.5. Each system architecture contained ideas on how the routing was performed, how the connector distances and positions were configured, and in what spatial configuration this would be carried out.

Table 4.5: Overview of the eight system architecture ideas generated during the first idea generation phase

System	Description
Spaced pin board	Board with uniform pins where the harness is routed around pins in variant-specific configurations.
Pin impression tool	Inspired by a pin-impression toy, where routed wires press down pins, creating a shape that holds the harness in place for wrapping.
Vacuum hole board	Vacuum board with suction holes that hold the harness in place during routing.
3D printed walls	Pre-printed walls prepared before routing begins, which group wires together according to their respective branches.
Gel substrate	Thick gel routing, where the gel holds the harness in 3D space, allowing branches to be routed on different vertical levels instead of being confined to a single two-dimensional plane.
Multi-level gantry system	Connector holders are configured on gantries in a 3D space. The gantries are positioned at varying lengths and heights, allowing the wiring harness to be configured in multiple ways depending on the variant. Different branches can be routed on different vertical levels instead of being confined to a single two-dimensional plane.
Connector onto terminal	Implements the specific case where the wire is fixed in position (2.2.1a), requiring the connector housing to be pushed onto the terminal (3.2.1a). Wires are placed and fixed, after which the connector housing is pushed onto each terminal, processing one branch at a time.
Automated movable connectors	Connectors are placed and fixed on independently movable connector holders on a plane. After each terminal is mated to its corresponding connector housing perpendicular to the plane, the grouped holders move to their designated positions to form the complete harness.

These eight system architectures were then carried forward to the initial screening phase, where they were evaluated and narrowed down using a Pugh matrix.

4.4.2 System Architecture Idea Screening with Pugh

A system-level screening was conducted to eliminate fundamentally weak or impractical ideas at an early stage. To enable a structured comparison, two instances of a Pugh matrix with different references were used to evaluate the system architectures ideas.

The evaluation was based on six criteria derived from the requirement specification. The relationship between each criterion and its underlying requirements is shown in Appendix E. *Feasibility* considers the technical viability of each idea, including manufacturability and required technology maturity. *Low complexity* reflects the

simplicity of the system in terms of components, assembly, and operation. *Expandability* assesses the ability of ideas to be adapted to different sizes without significant redesign. *Compatibility* evaluates how well the ideas can integrate with existing systems and interfaces. *Reconfigurability* refers to adapting the system to different harness variants without significant redesign. *Accuracy* refers to the precision and consistency with which the system performs its intended function. Both instances are shown below (see Table 4.6 and Table 4.7).

Table 4.6: Pugh matrix evaluation of system architecture ideas with spaced pin board as reference

	Ref (Spaced pin board)	Pin impression tool	Vacuum hole board	3D printed walls	Gel substrate	Multi-level gantry system	Connector onto terminal	Aut. movable connectors
Feasibility	0	-1	-2	0	-2	-1	-1	-1
Low complexity	0	-1	1	-1	1	-2	-1	-2
Scalability	0	0	-1	-1	1	-2	0	-1
Compatibility	0	0	1	0	-1	0	0	0
Reconfigurability	0	-1	0	-2	0	1	0	1
Accuracy	0	1	-2	2	-1	1	N/A	N/A
Total	0	-2	-3	-2	-2	-3	-2	-3

Table 4.7: Pugh matrix evaluation of system architecture ideas with pin impression tool as reference

	Spaced pin board	Ref (Pin impression tool)	Vacuum hole board	3D printed walls	Gel substrate	Multi-level gantry system	Connector onto terminal	Aut. movable connectors
Feasibility	1	0	-2	1	-2	0	1	0
Low complexity	1	0	1	2	2	-2	-2	-1
Scalability	0	0	-1	1	1	-1	-1	0
Compatibility	0	0	-1	-1	-1	-1	-2	-1
Reconfigurability	1	0	1	-2	2	1	0	0
Accuracy	-1	0	-2	0	-2	1	N/A	N/A
Total	2	0	-4	1	0	-2	-4	-2

As shown in the matrices, none of the alternative system ideas provides a clear improvement over the spaced pin board. Consequently, all system ideas that performed worse were eliminated at this stage. Although some systems showed strengths in individual criteria, these were not sufficient to outweigh their overall performance. Notably, the elimination of the system where the connector housing is pushed onto the terminal also led to the removal of functions 2.2.1a and 3.2.1a from the function tree.

4.4.3 Idea Generation within the Remaining System Architecture

Keeping the spaced pin board as the core system architecture, all idea generation and subsequent ideas were developed within that design space. This iteration of idea generation was more focused on generating means for the lowest hierarchical sub-functions in the function tree (see Figure 4.3) with the exception of functions 2.2.1a and 3.2.1a. The ideas were sketched (with descriptions when necessary), and each idea was linked to the function it fulfils based on the function numbering. After some time, a pattern became apparent: the ideas for some functions were interdependent and closely related to those for other functions. And as a result; functions were regrouped into nine new defined subsystems and the function tree was updated to better fit this (see Figure 4.6).

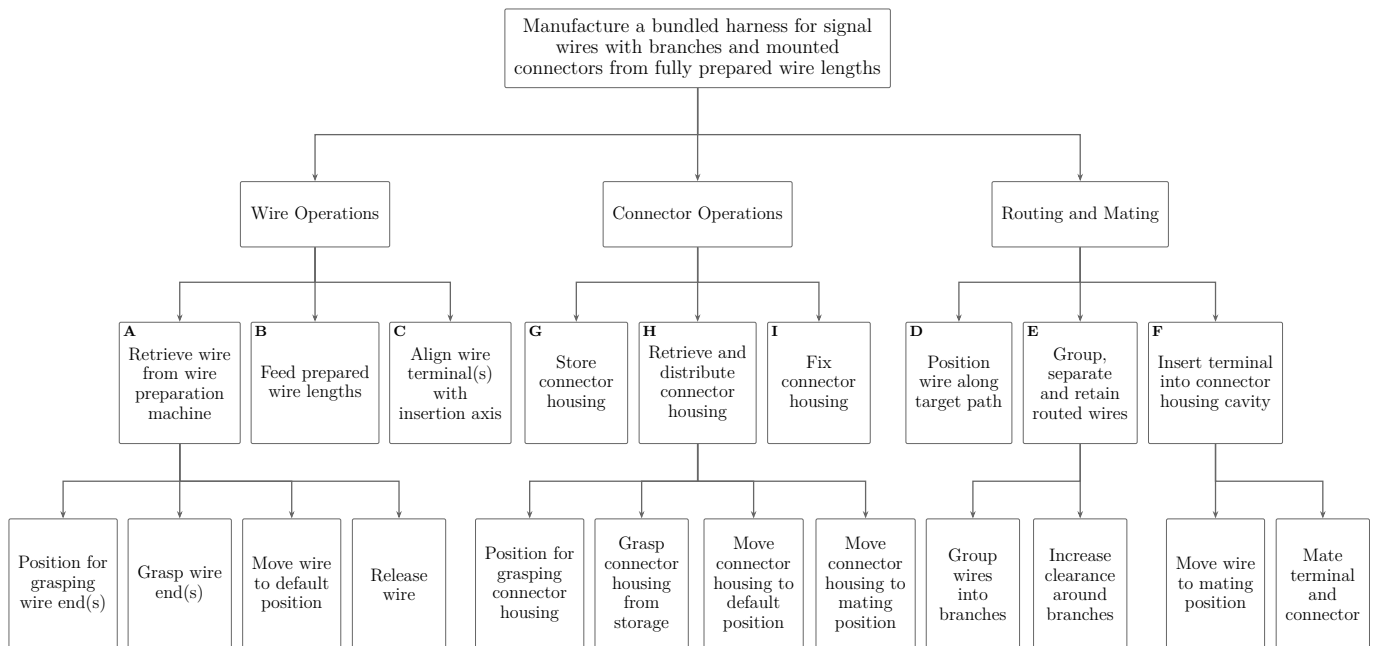


Figure 4.6: Updated function tree showing all three categories of operations and the nine subsystems, each with their respective functions

The new structure, top-down, begins with wire operations, where subsystem A retrieves the wire from the previous wire preparation step. This subsystem has four functions: positioning for grasping, grasping one or both ends, moving the wire to a

defined default position, and releasing the wire. Subsystem B feeds the wire to gain proper control and prepare it for routing and mating. Finally, subsystem C aligns the terminals with the insertion axis of the connector housing cavity.

The second part of the system's architecture is connector operations, where the storage of connector housings is decoupled from its previous placement into an independent subsystem G. Subsystem H is retrieving and distributing the connector housings, which is done by fulfilling four functions, first positioning the grasp, then grasping the connector housing from the storage, then moving it to an arbitrary default position, and finally moving it to the mating position where it will be fixed by subsystem I.

The third part of the system's architecture is routing and mating, where wire operations and connector operations interact to manufacture a bundled harness. This part consists of three subsystems. First, subsystem D performs a new function: positioning the wire along the target path defined by the current harness being manufactured. In the current system architecture, this function is essential for the solution to accomplish its task. Subsystem E addresses the grouping, separation, and retention of routed wires. This includes routing the wires into branches while maintaining clearance in order to support the next stage of *Adding Wrappings*. Finally, subsystem F involves the insertion of the terminal into the connector housing cavity, including moving the wire to mating position and terminating them through mating.

In total 49 subsystem ideas were generated across the nine subsystems. These are listed in Appendix D with brief descriptions.

4.4.4 Concept Synthesis with Morphological Matrix

Based on the subsystem ideas presented in Appendix D, a morphological matrix was constructed to systematically combine subsystem ideas into complete system concepts.

Subsystem	Subsystem Ideas						
Retrieve wire from wire preparation machine	A1	A2	A3	A4			
Feed prepared wire lengths	B1	B2	B3	B4	B5		
Align wire terminal(s) with insertion axis	C1	C2	C3	C4	C5	C6	
Position wire along target path	D1	D2	D3	D4	D5	D6	
Group, separate and retain routed wires	E1	E2	E3	E4	E5	E6	E7
Insert terminal into connector housing cavity	F1	F2	F3	F4			
Store connector housing	G1	G2	G3	G4	G5		
Retrieve and distribute connector housing	H1	H2	H3	H4	H5	H6	H7
Fix connector housing	I1	I2	I3	I4	I5		

Figure 4.7: Morphological matrix of the nine subsystems and their generated subsystem ideas, with five representative concepts highlighted

One subsystem idea from each row was selected and combined across all nine subsystems. The ideas could be combined freely, but subsystems A, B, C, and F tended to be combined in a tool head controlled by subsystem D, moving across an assembly table populated with subsystem E and I, and interacting with subsystem H with G being somewhat decoupled. These relations are mostly dependent on the selected system architecture.

Some combinations emerged iteratively during different stages of development, as concepts were refined and recombined over time. Although new concepts were added throughout the Concept Synthesis and Screening process, we can make the simplification that all concepts have been present from the start. Thus, the combined concepts shown in the morphological matrix are intended to help the reader follow the authors' reasoning, not as an exhaustive list of all combinations evaluated. For the reader's convenience, five representative concepts are highlighted to illustrate the screening methodology and the reasoning applied at each stage.

Additionally, a sketch of the red concept is shown in Figure 4.8 and an illustration of the green concept in Figure 4.9 below for the reader's convenience.

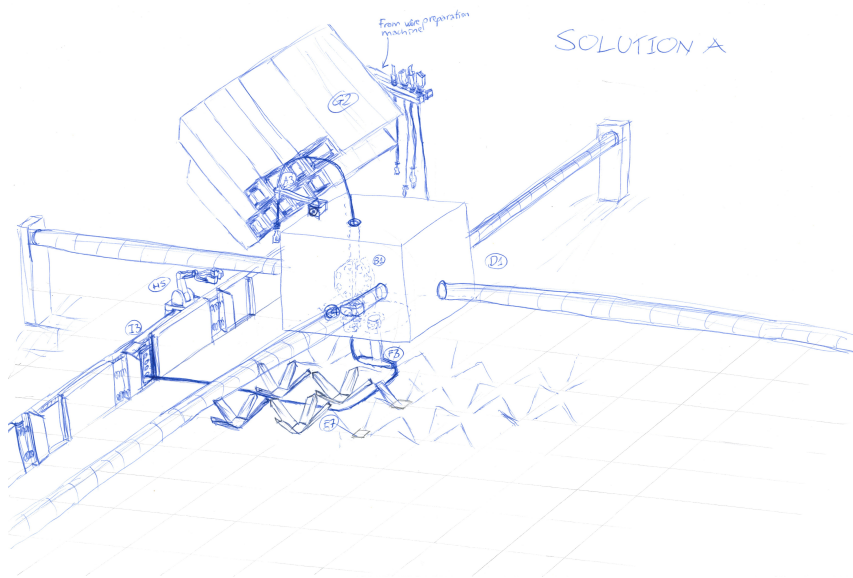


Figure 4.8: Concept A, also referred to as the “red” concept

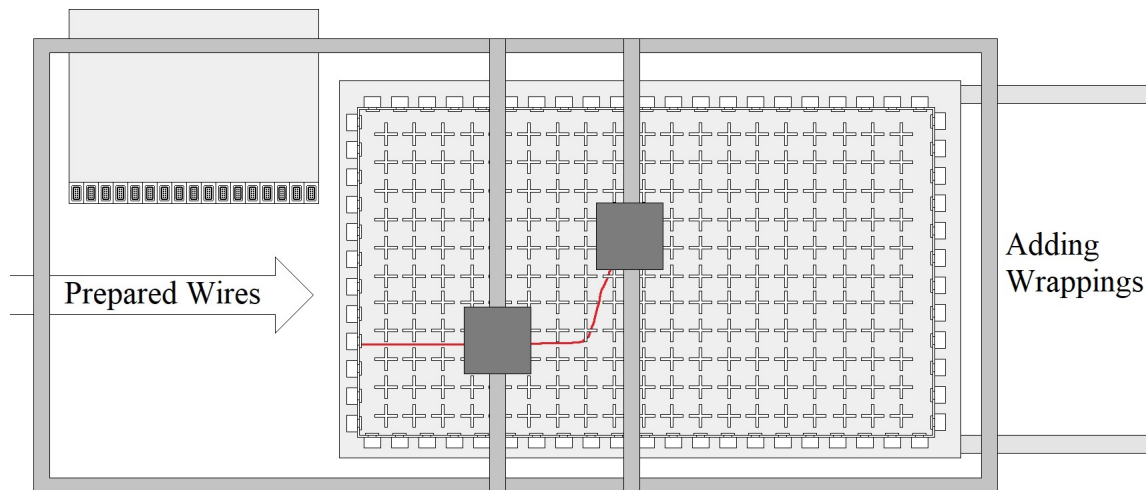


Figure 4.9: The “green” concept illustrated from above

4.5 Concept Screening

The synthesised concepts are evaluated against the requirements and desires to systematically remove concepts that in the first stage don’t fulfil the requirements, and in the second stage that fulfil the desires worse than other concepts. This process begins with an elimination matrix removing concepts that do not meet requirements, followed by iterative refinement of the morphological matrix, followed up by the utilisation of Pugh matrices to further remove those concepts that fulfil less desires than other concepts.

4.5.1 System-Level Concept Screening with Elimination Matrix

From the configured combinations, an iterative elimination process was applied. Each combination was evaluated against the requirements, with Table 4.8 showing the selected, directly verifiable requirements. The strictest requirements were placed at the far left of the elimination matrix to quickly identify deficiencies early on. Concepts that failed to meet any requirement were eliminated, and the non-compliant subsystem idea was traced and excluded from subsequent combinations to prevent repeated evaluation of the same failure. This process repeated until consistent results were achieved across iterations, with no new non-conformances identified. A total of 15 subsystem ideas were eliminated, and dependencies and conflicts between subsystems were also identified. Table 4.8 shows the elimination evaluation for the five representative concepts highlighted in the morphological matrix.

Table 4.8: Elimination matrix of the five representative concepts

		Manufacture a WH for signal wires	Manufacture according to defined design	Carry out precise operation	Handle MCP 1.5 and 2.8 terminals	Handle 6 selected connector housings	Non-conforming WH $\leq$ limit	Cross-sectional area: $0.75-2.5 \text{ mm}^2$	WH diameter $\in 3\text{mm to } 50\text{mm}$	Grommet thickness $\leq 5.9\text{mm}$	Wire diameter $\geq 0.6\text{mm}$	Stiff length $\geq 32.8\text{mm}$
Blue	—											
Red	+	+	+	+	+	+	+	+	+	+	+	+
Orange	+	?	+	+	+	+	+	+	+	+	+	+
Green	+	?	+	+	+	+	+	+	+	+	+	+
Purple	+	?	+	+	+	+	+	+	+	+	+	+

Of these five representative concepts, four passed the screening and were carried forward, while one was eliminated. The Orange, Green, and Purple concepts received a questionable rating on the requirement “Manufacture according to defined design”, meaning it was unclear whether they could manufacture certain harness variants. They were still carried forward for further evaluation. The Blue concept was eliminated for the reasons explained below.

4.5.2 Reasons for Elimination

Three categories of reasons were identified for why concepts were eliminated across the screening process:

1. **Incompatibility:** Subsystem ideas that could not function together due to physical interference, conflicting principles, or mismatched interfaces were eliminated.
2. **Missing dependencies:** Subsystem ideas that required other specific subsystem ideas to function were eliminated when those dependencies were not satisfied.
3. **Requirement not fulfilled:** Subsystem ideas that did not meet the required performance or specification targets, or are technologically immature were eliminated and removed from the morphological matrix altogether.

Among the five concepts, only one was eliminated during this screening. The elimination reasoning for this concept, along with the implications of this decision, is presented below.

Incompatibility: The concept relies on E5 (pins with sponge top) together with I5 (traditional connector holders). The sponge tops cover a large area of the assembly board, which physically obstructs the adjustment of traditional connector holders

when reconfiguring for different harness variants. This makes the system inflexible and unsuitable for high-mix production environments where frequent changeovers are required.

Missing dependencies: Additionally, the concept depends on H2 (spring gripper with a 1D gantry) for retrieving and distributing connector housings. However, (I5) traditional connector holders can be positioned anywhere on the board, not only at the edges. The gripper requires I3 (table edge system) to function correctly, but since the holders are not edge-limited, the gripper cannot reliably reach or distribute connector housings in many configurations, leading to operational failures. No subsystem ideas were eliminated as a result of these interactions, but valuable subsystem-specific information was uncovered.

Requirement not fulfilled: The concept uses F1 (direct feed) for terminal insertion, which cannot handle wire end 2 without significant redesign, which would result in a different subsystem idea altogether. This means the concept cannot complete the full insertion sequence required to manufacture a complete harness. Consequently, F1 was eliminated as an idea for subsystem F, traced, and excluded from all subsequent combinations.

The morphological matrix was updated considering the eliminated subsystem ideas, and the remaining ideas were kept for the next stage in the process.

4.5.3 Subsystem Idea Screening with Pugh Matrices

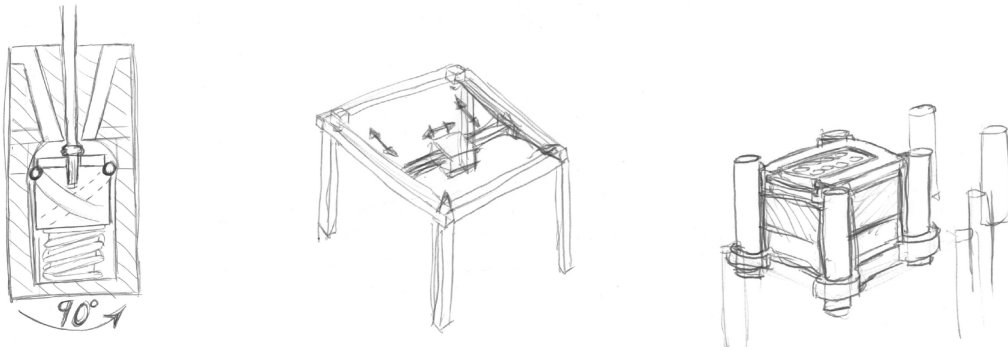
As a large number of subsystem ideas still remained at a relatively late stage in the thesis's time frame, it was considered unrealistic to synthesise a large number of concepts and screen these in a single Pugh matrix. To further screen ideas for subsystems within each subsystem, Pugh matrices were instead developed at the subsystem idea level, for all nine subsystems. Each matrix evaluated the alternative subsystem ideas against the relevant criteria derived from the requirements specification. The criteria vary depending on the needs of the specific subfunction. An example is that for subsystem C terminal alignment, compactness is crucial for the ability to integrate these into the tool head, while for subsystem A wire retrieval, this is lower priority, as it can be mounted on the outside of the tool head. The complete Pugh matrices are provided in Appendix F.

Although all subsystems were evaluated, here only the Pugh matrices that directly affected the eliminated concept are discussed to illustrate the reasoning behind the elimination. The orange concept was eliminated as a result of subsystem ideas being eliminated from multiple subsystems:

Table 4.9: Summary of eliminated subsystem ideas after elimination of the representative orange concept

ID	Sub-solution	Reason for elimination
C5	Dip aligner	Poor performance across multiple criteria; lowest total score in both reference configurations
D4	CoreXY gantry	Negative total score compared to reference; underperformed in low complexity, accuracy, and expandability
E4	Hybrid pins	Consistently poor performance in wire retaining, routing ease, and harness flexibility; lowest or near-lowest ranking across references

The subsystem ideas are also presented as sketches below, in Figure 4.10.

**Figure 4.10:** Subsystem ideas C5 (Dip aligner), D4 (CoreXY gantry) and E4 (Hybrid pins), respectively

C5 (Dip aligner) was eliminated due to performing worse than its counterparts across multiple criteria. Despite being entirely mechanical, the mechanism would be inherently complex, requiring many components and different dedicated aligners for each terminal size. It would also require other systems to adjust to its dip-and-raise movement. Although it performed equally to the winning subsystem ideas in speed, it would be slower than feed-through aligners. The dip aligner performed worse in reconfigurability, compactness (a high-weight criterion due to space constraints), and reliability (also high-weight due to quality requirements). It was evaluated as far less reliable than the visual aligner and the rotating pressure aligner, which do not rely solely on mechanical mechanisms.

D4 (CoreXY gantry) was eliminated due to performing worse than the reference Cartesian CNC system across multiple criteria. The CoreXY system requires a more complex belt arrangement, increasing mechanical complexity and maintenance compared to the Cartesian CNC system. For expandability, Cartesian CNC systems can be easily scaled, whereas CoreXY systems require a more complex redesign. Although the CoreXY gantry performed better in speed due to its lower moving mass, this single advantage was not sufficient to outweigh its shortcomings in low

complexity, accuracy, and expandability.

E4 (Hybrid pins) was eliminated due to its consistently poor performance across both reference configurations. The design requires a two-step assembly process, connector placed on holder, then holder placed on straight pins, which adds unnecessary tooling and process steps before the assembly can be placed on the pin board. Combined with its vertical connector cavity orientation, this complexity negatively impacted wire retention and ease of routing. Furthermore, different connectors would require different holders, limiting harness flexibility and increasing tooling inventory. Although the removable holder design made harness removal easier, this single advantage was insufficient to outweigh its weaknesses. With both references, E4 scored the lowest overall.

I1 was not eliminated and performed well within its own subsystem screening. However, due to its dependency on E4, and since E4 was removed, I1 must be redesigned to address the faults introduced by this missing dependency.

4.5.4 Concept Screening with Pugh Matrix Using Desirables

The three remaining representative concepts were evaluated against desirable criteria using a series of weighted Pugh matrices with various references. Table 4.10 presents the matrix, with one concept selected as reference for comparison. Certain desirable criteria were excluded, as they either showed no difference between concepts or were too early to assess without physical prototyping.

Table 4.10: Final Pugh matrix comparing three representative concepts

Desires	Weight	Ref (Red)	Green	Purple
No human involvement in manufacturing	5	0	0	–
Add passives without manual harness handling	4	0	0	0
Reduce manufacturing time by 15 %	5	0	–	–
Reduce manufacturing cost by 15 %	5	0	+	–
Ability to route and handle long wires	2	0	0	0
Handle all 122 possible connectors	2	0	0	+
Minimise the use of custom-built parts	1	0	0	–
Integration with adjacent manufacturing systems	5	0	0	–
Total score		0	0	-19
Ranking		1	1	2
Further development		Yes	Yes	No

No human involvement in manufacturing: There were no inherent differences between the red and green concepts, with the machine operator as a baseline. However, it was evaluated that the purple concept would need more human involvement due to I1 (vertical pin-connector table). Although I1 was redesigned so that it could

be independent of pin design and thus function with the remaining subsystem ideas from subsystem E, no way was found to remove the pre-assembly step of adding these holders. As the system architecture currently looks, it would require that a human places the connector holder into the mounting interface on the table or pin before subsystem H can retrieve and distribute the housing.

Add passives without manual harness handling: There were no inherent differences between the red concept and the other concepts, as all representative concepts managed this.

Reduce manufacturing time by 15 %: Both the green and purple concepts performed worse against the red concept. At this stage certain subsystem ideas in subsystem H were iteratively redesigned and combined together with subsystem F so that the same subsystem can be used for both inserting the terminal, retrieving, and distributing the connector housing. The green concept had this benefit; however, it did not change the fact that D1 (Cartesian CNC system) can handle one task at a time and not both simultaneously. The red concept has H5 (robotic gripper with 1D gantry) that can retrieve and distribute connector housings simultaneously while D1 can focus entirely on the wire side of operations, so the red concept scored higher.

Reduce manufacturing cost by 15 %: The green concept performed better than the red concept, this was due to it having two subsystems less: B5 (no feeder) and subsystem H being integrated into or made redundant by subsystem F. It is also important to mention that this concept incorporates two tool heads on its D1 as well as two F3 (integrated router and gripper), one for each tool head. Although this increased the cost, it was still evaluated as costing less. The purple concept scored lower because it needs additional tooling for I1 as well as more manual labour.

Ability to route and handle long wires: The green concept has two grippers that handle the wire, and the free loose section in the middle may be prone to interference if the wire is too long. This could result in the wire getting stuck on pins. There is no inherent difference between the red and purple concepts as they handle the wires the same way through a feeder. However, if the wire is too long it could result in wire slack and that wire end 2 hangs out from the top of the feeder while wire end 1 is being handled which can lead to interference. For these reasons both concepts scored the same against the red concept.

Handle all 122 possible connectors: The green concept has the same subsystem idea I3 (horizontal table edge system) for fixing the connector housings as the red concept and can therefore handle the same connector housing types. The purple concept has I1 which enables a wider range of connector housing configurations, since it is custom-built and not constrained by the board's dimensional limitations like I3 is, thus scoring better than the red concept.

Minimise the use of custom-built parts: No inherent differences between the green concept and the red concept were found. The purple concept has more custom-built parts due to the I3 tooling and therefore received a lower score in comparison.

Integration with adjacent manufacturing systems: The H5 gantry system railing may create minor restrictions during integration with other manufacturing systems. Similarly, the green concept requires that, upon completion of wire preparation, the wire preparation machine has control over both ends, enabling the two grippers to each grip one wire end. Both concepts have restrictions that cancel each other out during evaluation. The purple concept has I1 where the terminals are inserted vertically creating a bend down to the pins where it is routed. This makes it significantly more difficult to incorporate *adding wrapping*, which is why it received a lower score compared to the red concept.

Overall, the purple concept performed significantly worse against the desirable criteria than the other two concepts and was consequently eliminated. The green and red concepts achieved the same total score and were both carried forward for further evaluation.

4.6 Rapid Prototyping of Subsystem Ideas and Principles

At this stage, several questions remained regarding specific ideas, system principles, and interactions between subsystems. To address these uncertainties, selected subsystem ideas and system components were modelled in CAD using Creo Parametric and then printed on a Bambu Lab X1 3D printer. PLA, PETG, and TPU filaments were used to produce prototypes with varying mechanical properties, allowing different subsystem ideas to be tested. A CNC test rig was also used for testing. Not all prototyping is presented here, only a selection is shown to illustrate the methodology and the iterative redesign process.

4.6.1 Rapid Prototyping of Subsystem Ideas

The remaining ideas within subsystem E were among those that needed to be tested as ideas E3 (pins with rubber flaps), E6 (curved flexible pins) and E7 (straight 45° angled flexible pins) all performed well in the theoretical methods. Therefore, these were selected for rapid prototyping to evaluate their performance in wire retention and routing.

E3 (Pins with rubber flaps): This concept consists of pins equipped with four rubber flaps, each oriented at 90 degree intervals, extending in all directions to create a small gap between the opposing pins. The concept relies on the gripper of subsystem F pressing the flaps open as it passes through while carrying the wire. The flaps then return to their original position once the wire has passed, thereby retaining the routed wire in place. During testing, the concept worked; however, it had some minor issues. Occasionally, the gripper was unable to pass through because the flaps were too rigid due to their large cross-section (see Figure 4.11).

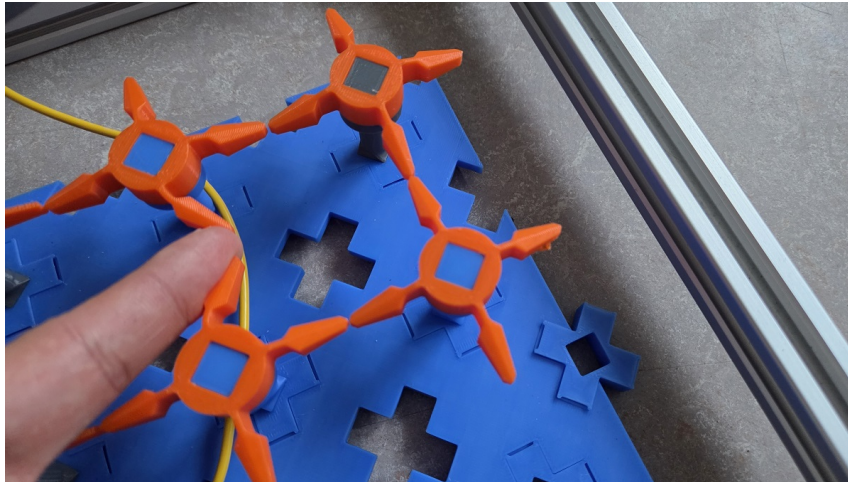


Figure 4.11: Rapid prototype E3 tested

E5 (pins with sponge tops): Initially, the fate of this idea was marked as “TBD” (to be determined) in the Pugh matrix for subsystem E, as the theoretical information available was deemed insufficient to determine the minimum score needed for progression, leaving uncertainty about whether to eliminate the idea. Therefore, it was determined that the idea should be tested to make a more realistic and fact-based decision. However, during testing of the other ideas for subsystem E, it became clear that this idea would not be able to facilitate adding wrappings, as the large sponge tops would lead to accessibility issues and act as obstacles. For this reason, E5 was eliminated before a prototype was built.

E6 (curved flexible pins): This concept uses curved pins that must be pressed downward to create a gap between the activated pin and the opposing pin, allowing the wire to be inserted beneath the pins. The gripper from subsystem F is designed to perform this pressing action. This procedure is repeated for each pin, creating a locking mechanism that secures the routed wires in place. During testing, several issues with the idea were quickly identified. When the activated pin was pressed downward, it interfered with the opposing pin, preventing the wire from being inserted between them. This interaction can be seen in Figure 4.12 below, where the activated pin overlaps with the opposing pin.

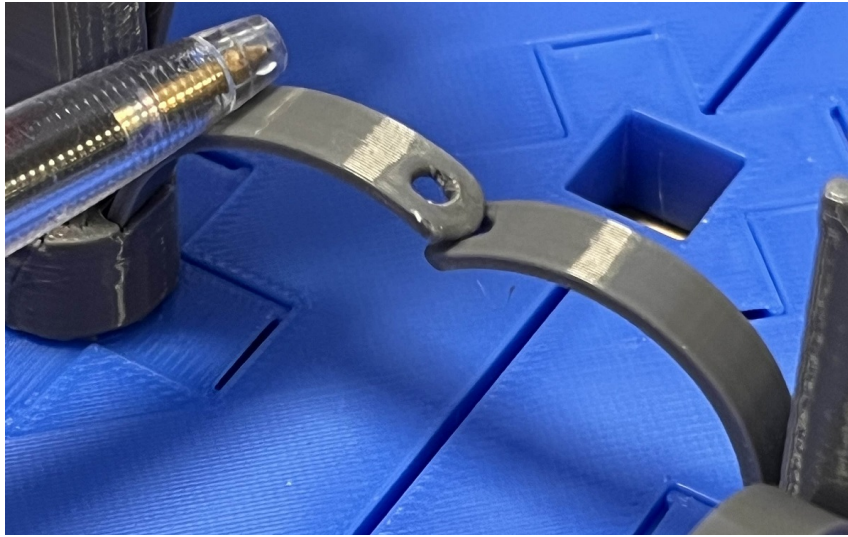


Figure 4.12: Rapid prototype E6 tested

As the intended functionality of the subsystem idea could not be achieved during testing, the idea was eliminated at this stage of the development process.

E7 (Straight 45° angled flexible pins): This concept consists of pins that extend straight upward at a 45 degree angle. Like E3, it relies on the gripper from subsystem F pressing the pins open to allow passage while routing the wire, after which the pins return to their original position. The concept is therefore functionally identical to E3, differing only in material characteristics and pin geometry. During testing, E7 worked as intended and performed similarly to E3. However, the pins proved to be both too short and too large in cross-section, which occasionally prevented the gripper from passing through cleanly (see Figure 4.13).

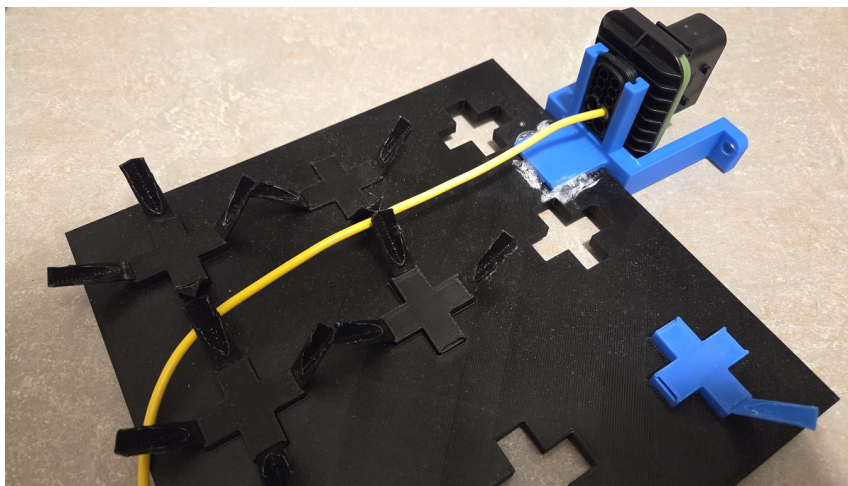


Figure 4.13: Rapid prototype E7 tested

4.6.2 Iterative Redesign of Subsystem Ideas

Based on the initial prototyping results, E3 and E7 were redesigned. E3's flaps were thinned to reduce rigidity (see Figure 4.14), while E7's pins were lengthened with

a reduced cross-section to improve flexibility. Both modifications aimed to allow the gripper to pass through consistently. When redesigned and tested again, E3 performed exactly as intended with no issues. E7, however, still exhibited similar problems due to the inherent rigidity of its design.



Figure 4.14: Comparison between initial and updated E3 idea

As the intended functionality could not be achieved during testing, E7 was eliminated at this stage of the development process, leaving E3 as the only remaining idea for subsystem E.

4.6.3 Rapid Prototyping of System Principles

In addition to test individual subsystem ideas, certain system-wide principles required validation through prototyping. One of these was the examination of a longer deformable linear object between two points to determine whether any potential obstruction would occur. This case had a direct correlation with the green concept, where two tool heads are used.

The test was conducted on a CNC test rig using a printed tool head equipped with the gripper (see Figure 4.15). Due to the limitation of having access to only one head, one of the wire ends had to be held manually to simulate how it would behave in a real setting.

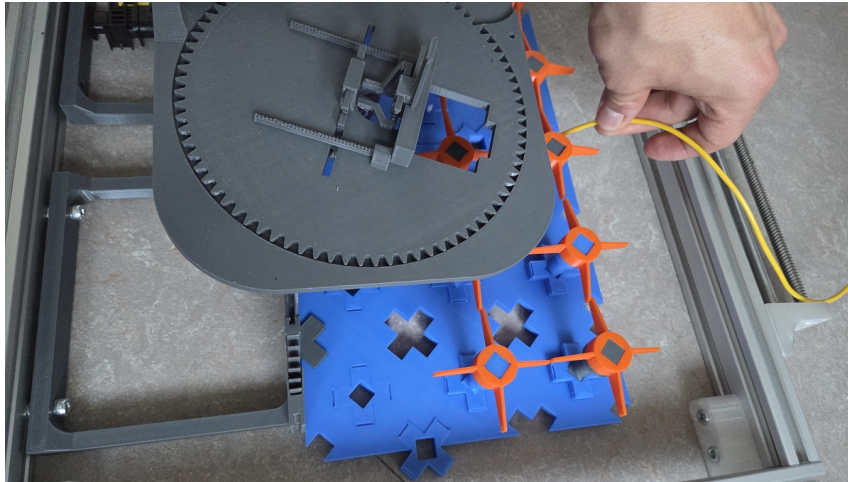


Figure 4.15: Simulating two tool heads by holding the other end

The test revealed distinct limitations depending on wire length. For shorter wires, the physical space between the two tool heads was insufficient to accommodate the sequence of inserting wire end 1, routing, and inserting wire end 2. For longer wires, the stretched wire formed too shallow an angle with the ground, causing obstructions with pins and loss of clearance (see Figure 4.16).

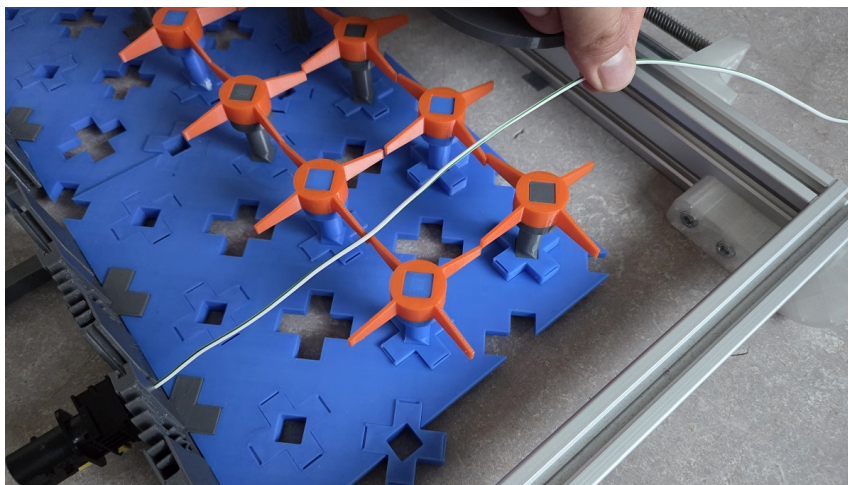


Figure 4.16: Simulation of the low angle between head 1 and head 2 of “green” concept

Another limitation of the green concept became apparent during the test. The two tool heads share the same CNC gantry and cannot pass each other. This becomes problematic for harness variants where the wire must be routed such that part of the wire ends up behind the gripper after inserting wire end 1. In such cases, the intended routing path cannot be executed because the tool heads cannot cross one another. One of these scenarios can be seen in Figure 4.17, where the sketch from a top-down view demonstrates that the dual tool heads and dual-gantry system cannot route the red wire along the blue path, as the gantries collide when gantry B attempts to guide the wire.

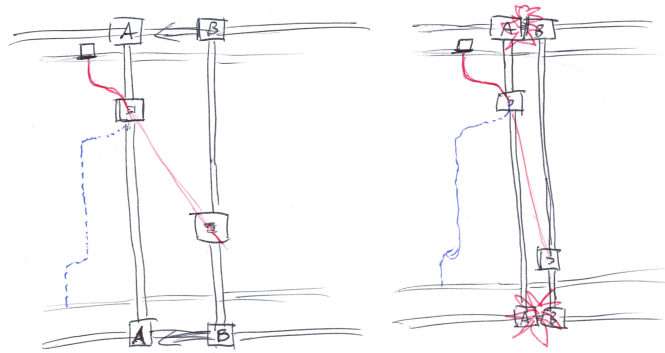


Figure 4.17: For certain routing directions, the two tool head gantries would need to cross each other, which is physically impossible

This is also demonstrated with the prototype in Figure 4.18 below.

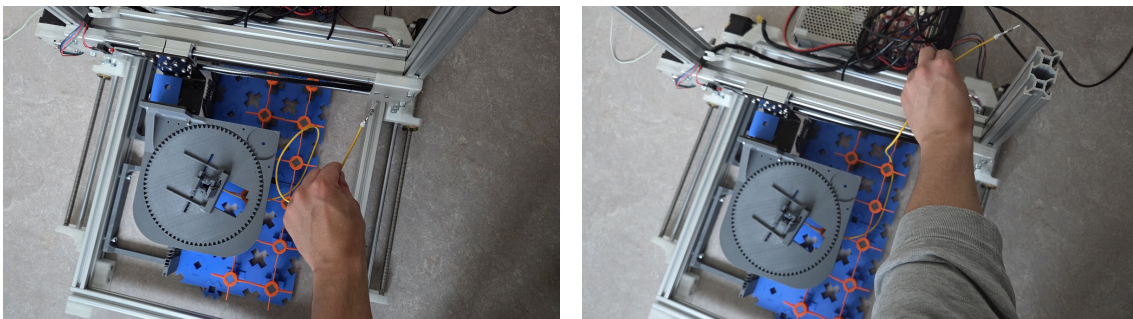


Figure 4.18: For certain routing directions, the two tool head gantries would need to cross each other, which is physically impossible

Another system principle that needed to be tested was the interaction between F3 (integrated router and gripper) and the terminal gripper after alignment. This interaction occurs in the red concept. The tool head and its affected mechanisms were printed and tested to determine whether the interaction behaved as expected. The test concluded that it works; however, a limitation became apparent. The length of F3 depends on the size of the tool head, as it must swing upward 90 degrees to grip the aligned terminal and the wire (see Figure 4.19).

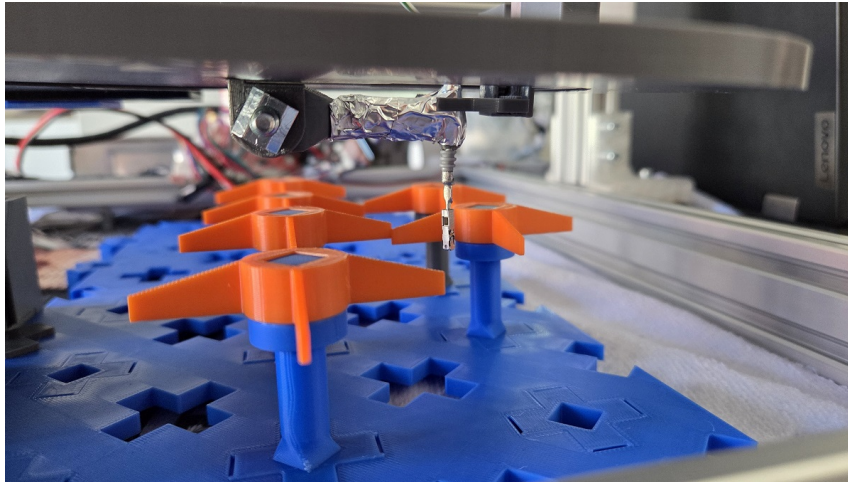


Figure 4.19: Depicting the “red” concept’s way of retrieving wire end

Another principle that was tested was the red concept’s ability to handle long wires where wire end 2 hangs out from the feeder creating wire slack and if there were any apparent obstructions due to this. This test was conducted on the CNC test rig with the 3D printed tool head where the wire were held in a way to resemble this scenario while routing wire end 1 (see Figure 4.20).

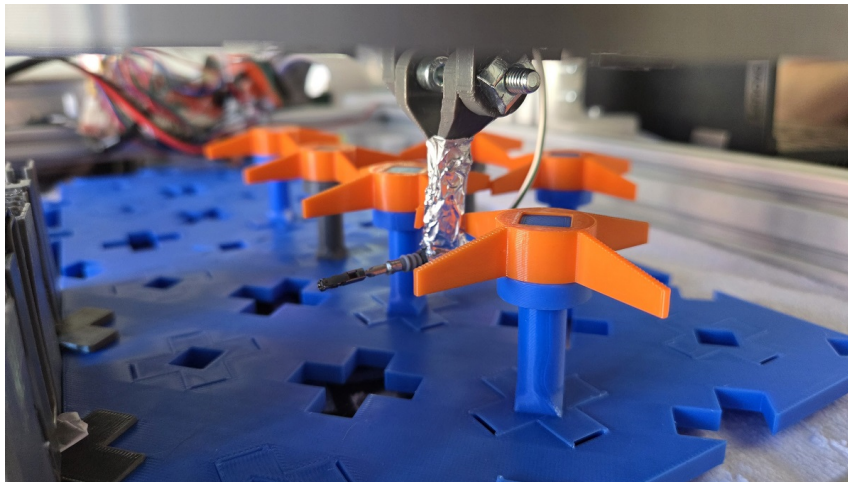


Figure 4.20: Testing of the “red” concept’s ability to route wires

It was concluded that this interaction did not pose a problem. However, due to the small sample size, further testing may be required in the future to simulate different stages of harness manufacturing with varying numbers of wires being laid out and with various harness variants, in order to determine whether this could become a potential error mode. Additionally, it was noted that alternative tool head designs might eliminate this scenario entirely; as a result, testing was concluded at this stage

Rapid prototyping resulted in the redesign of certain subsystems and the validation of system principles in different concepts. Although the green concept offers certain advantages, such as being able to route both ends simultaneously, it also has inherent constraints that limit its ability to manufacture certain harness variants. In the

elimination matrix presented in Table 4.8, this was set as a question-mark, meaning that more information would be needed to confirm whether the requirement can be fulfilled with the concept or not. Now, it has been confirmed that this question-mark is not fulfilled instead. Thus, since the green concept could not meet this requirement, it was eliminated at this stage. The red concept did not exhibit such faults and was therefore carried forward as the remaining concept, with E3 replacing the eliminated E7. The following chapter presents the resulting solution in detail.

5

Proposed Solution

The proposed solution consists of a Cartesian 3-axis CNC machine with a single tool head. This tool head is capable of retrieving prepared wires, routing one wire at a time and can also align wire terminals that are not rotationally symmetric. The routing of wires takes place on the routing board, which features plastic pins, in a grid pattern every 60 mm. The pins are capped with flexible flaps in a cross-shape, that meet the flaps of adjacent pins, thus creating a system where wires can be securely routed without becoming loose. A track runs around the perimeter of the board where a transport platform with a small robotic arm is capable of transporting connector housings. The housing storage consists of a modular and expandable system where the housings are gravity-fed in stacks by type and size. The transport system moves and places the housings in holders that are situated around the perimeter of the board, aligned in between the pins every 60 mm. The holders feature channels and compressive springs which the housings slide into and are secured by, respectively. Figure 5.1 provides an overview of the proposed solution.

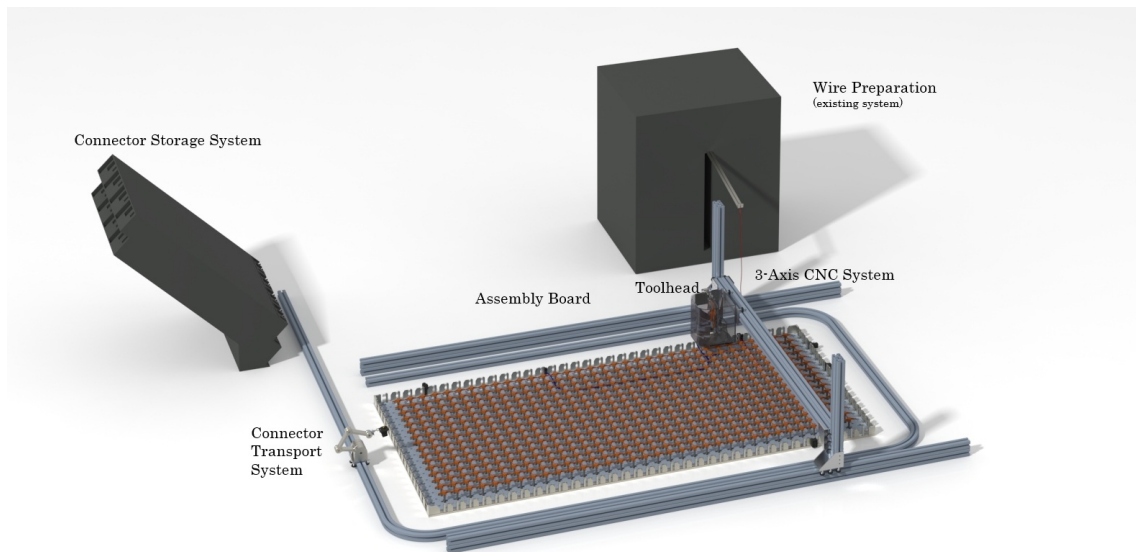


Figure 5.1: Overview of the proposed solution

5.1 System Architecture of the Proposed Solution

Prior to any operations, the harness design file that contains harness-specific information must be converted into a manufacturing file. Currently, this information is included in a X2ML file, which includes information regarding part numbers of wires, connector housings, passives and routing. This information must be converted into machine-adapted instructions that will control the routing, the wire preparation system, the connector housing preparation system, and any systems that come after the routing, with all systems working in synchronisation. This process is illustrated in Figure 5.2 and integrated into the overall system architecture shown in Figure 5.3.



Figure 5.2: Conversion of design file to firmware file

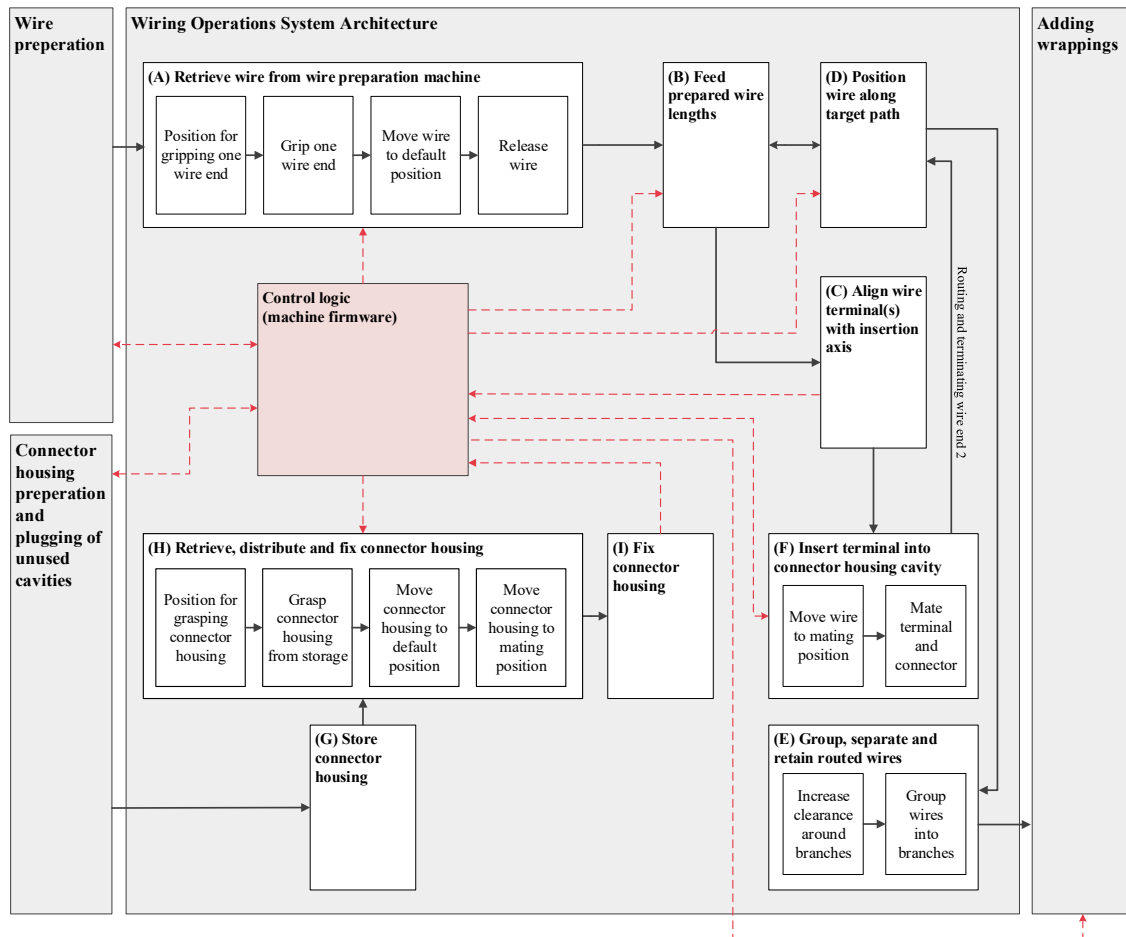


Figure 5.3: System architecture of the proposed solution including control logic

These adjacent systems transfer prepared wires and connector housings (with pre-plugged unused cavities) to the wiring operations system. Adding wrappings is also included to show where it would fit if integrated in the future. The architecture

includes all nine subsystems, the interactions between them, and the sequence in which functions are performed within each subsystem. The aforementioned control logic box is also included, as is essential for the solution to perform its intended function. Since this was outside the scope of this thesis, the control logic has not been explored beyond identifying where each system or subsystem may require signals from previous steps to initiate the next operation.

5.2 Explanation of the Functionality of the Proposed Solution

This section presents the functionality of the proposed solution which emerged from the iterative development and screening process described in the previous chapters. The routing process begins with the connector housing transport system moving to housing storage and retrieving the appropriate housing from the bottom of the stack (see Figure 5.4). The housings are in order and are pre-plugged in the unused cavities, in accordance with the manufacturing file and with the help of an existing connector plugging machine. Once the housing is retrieved, the rest of the stack drops down so that the next housing can be retrieved later.

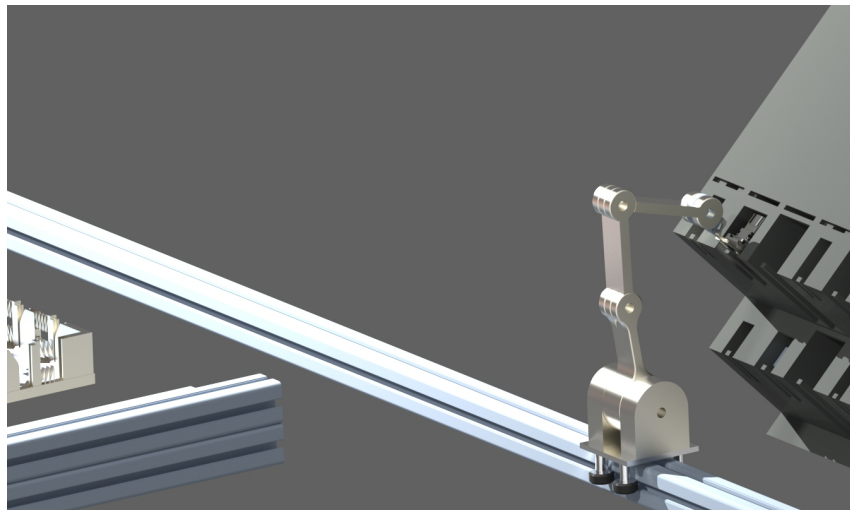


Figure 5.4: Connector housing is retrieved from the storage stack

The retrieved housing is then moved along the track around the routing table to the correct holder on the table perimeter (see Figure 5.5). The gripper pushes down the housing into the holder, while the gripper releases, at the same time holding open the springed gate so that the housing can slide down into the holder (see Figure 5.6). Once it is in place, the gripper retracts, and the springed gate is released, clamping the housing in place. The gripper is moved back to the storage area along the track, ready to pick up the next housing that is needed for the harness. This process of retrieving and distributing should happen rather quickly, within a few seconds per housing. While the housings are being placed out, the routing process can start in parallel.

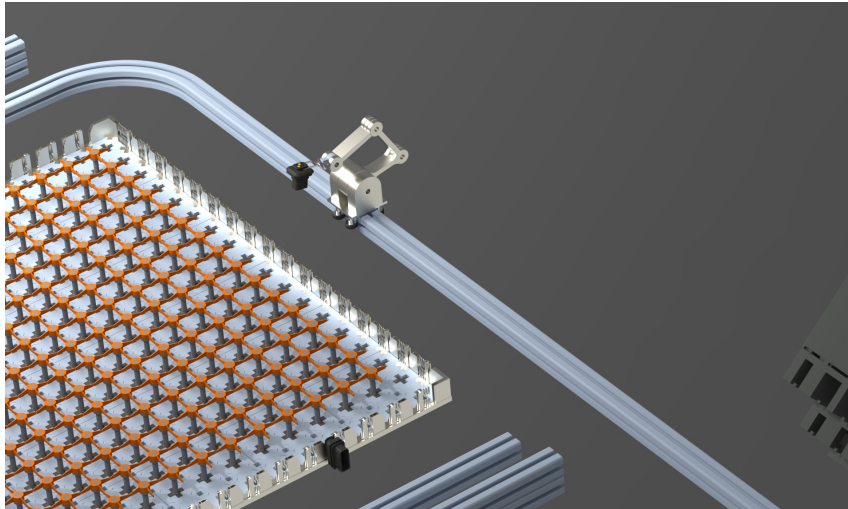


Figure 5.5: Connector is moved along the transport track to the appropriate holder

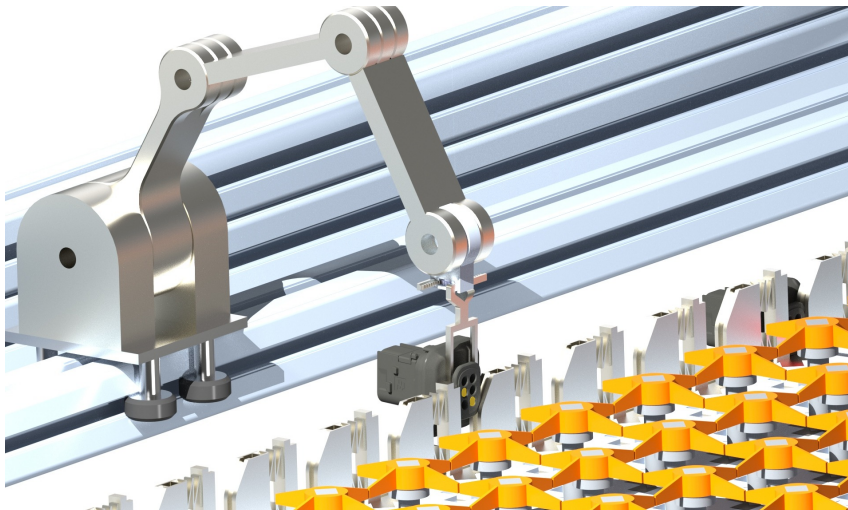


Figure 5.6: Connector is inserted into the springed holder

The routing begins with the tool head moving to the corner where the existing automated wire preparation machine outputs the prepared wire lengths. These wire lengths exit the preparation machine between two rails. If the wire preparation machine outputs wires differently, some redesign may be required. The wires should be outputted in the same order as the wires are routed. This should be managed by the manufacturing file that also controls the routing. Once the wire is outputted, the integrated wire retrieval arm (A), situated at the top of the tool head is articulated towards the wire preparation machine, opening the gripper and using the X-Y-Z Cartesian system to move the opened gripper around the wire (see Figure 5.7). The gripper then closes, lifts the gripped wire from the rail (or from an eventual other means of outputting), and the gantry system moves away from the retrieval position, now with the retrieved wire trailing (see Figure 5.8). The retrieval arm is articulated back 180 degrees and feeds to wire end into the tool head. The rest of the wire is proposed to be left trailing the tool head, however if this poses challenges, a system

handling the trailing wire would need to be developed. While the prepared wire is fed, the tool head starts to move toward the first housing.

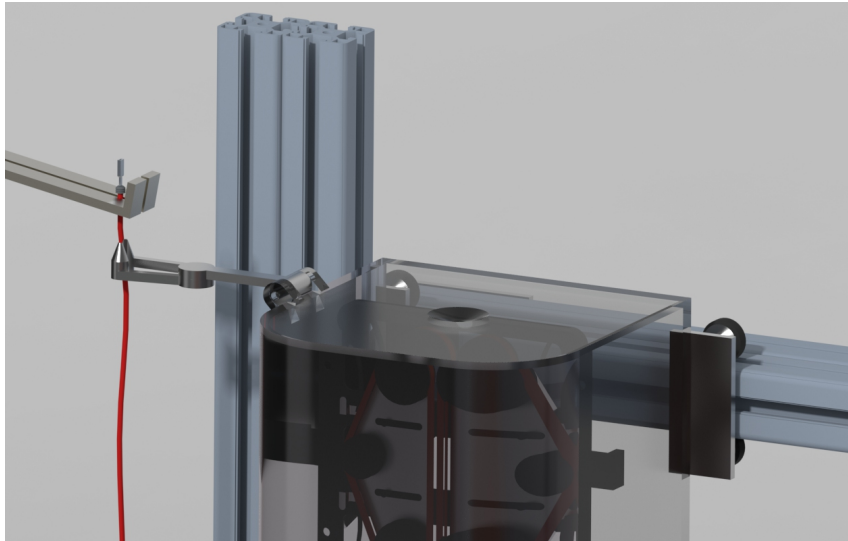


Figure 5.7: Retrieval of wire from preparation machine

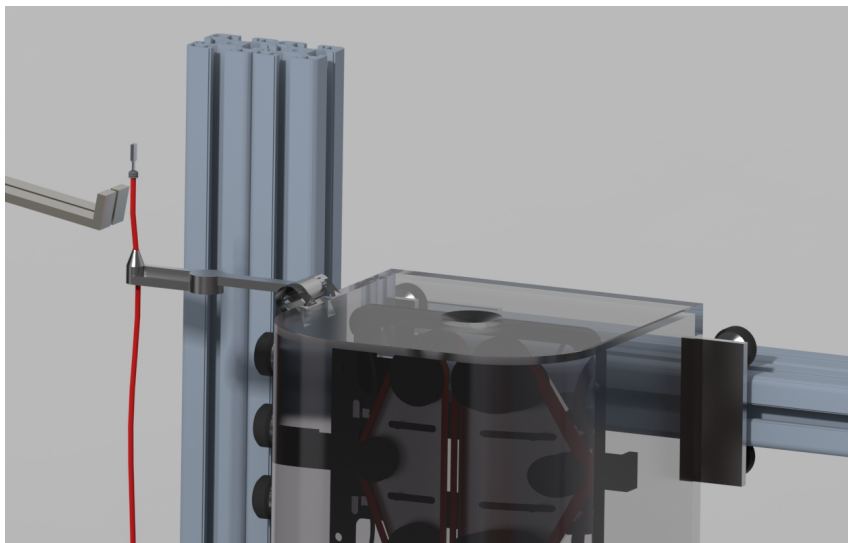


Figure 5.8: Wire is gripped and removed from the preparation machine

The tool head contains a belt feeder (B), two flexible driven belts that can feed prepared wires and are mounted with springs, adapting to various wire sizes (see Figure 5.9). Once the wire is gripped by the belt feeder, the retrieval arm disengages the wire and the terminal on the wire end 1 is fed until it is through the rotating gripper of the terminal aligner. The terminal needs to be aligned, and be kept aligned until the terminal is inserted into the housing cavity, for all terminals that are not rotationally symmetric. The terminal is gripped by a chuck-like rotational gripper and is rotated while the lower sensor of the visual aligner system (C) identifies the terminal's rotational position. The rotational gripper rotates the wire until the visual aligner system identifies correct alignment (see Figure 5.10).

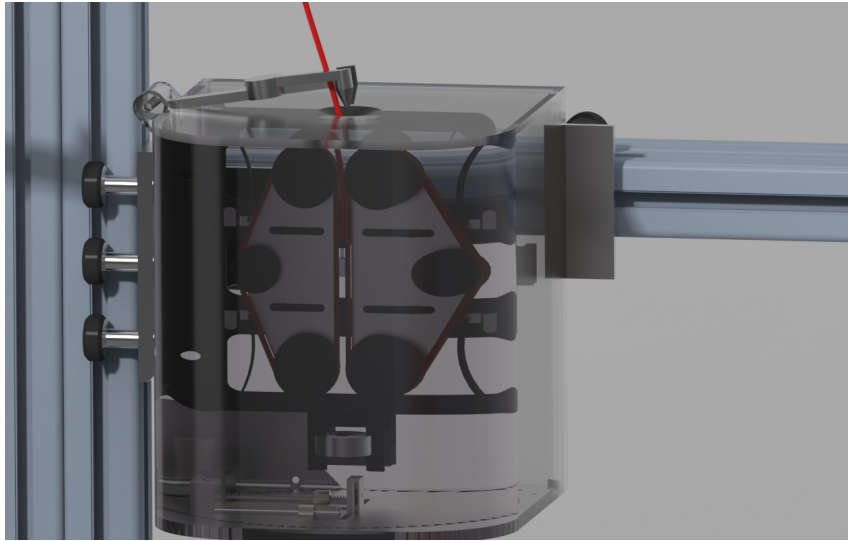


Figure 5.9: Belt feeder feeds the wire in unison with the rest of the system

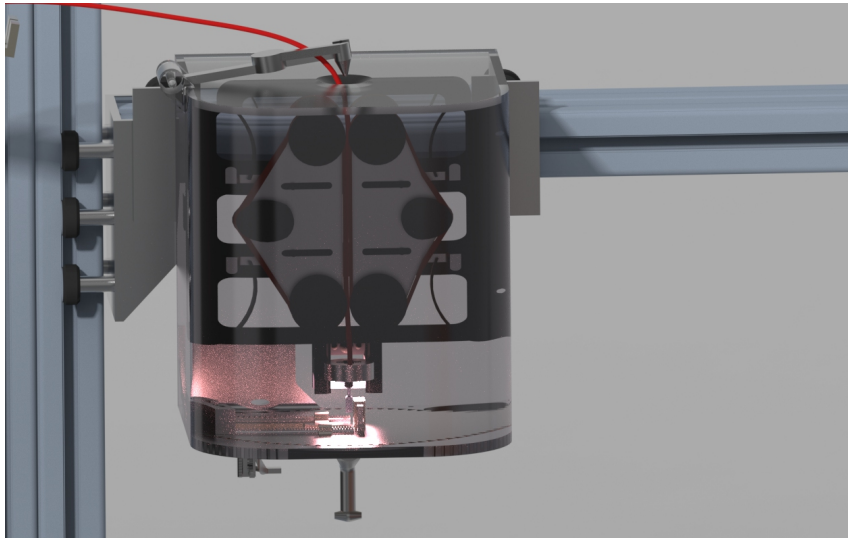


Figure 5.10: Terminal is gripped and rotated until the sensor determines that it is aligned

At this point, the terminal gripper moves to the aligned terminal gripping it, and the rotating gripper releases the terminal (see Figure 5.11). The terminal is moved downward and outward and the terminal gripper moves it down through the opening in the bottom of the tool head. Note that the terminal gripper was not one of the original subsystems but was added to make the terminal handling possible. The routing tool (F) is then moved up 90 degrees and grips the wire above the terminal (see Figure 5.12).

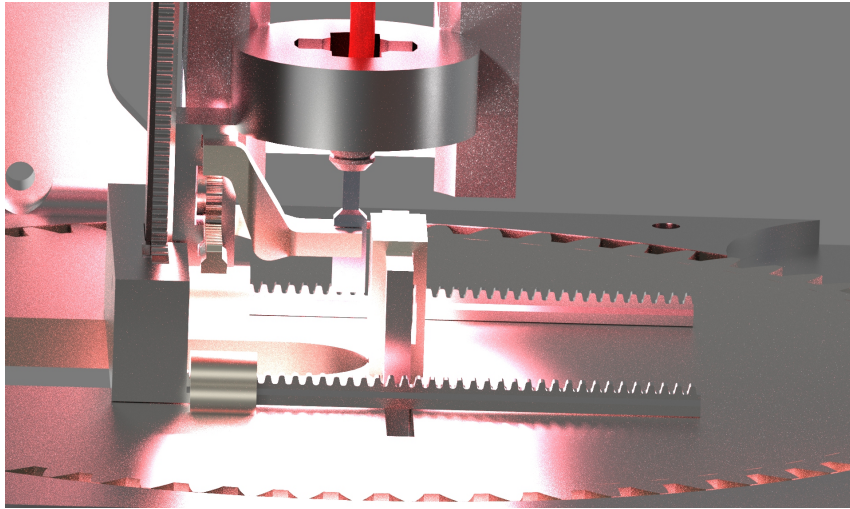


Figure 5.11: Aligned terminal is grasped by the terminal gripper

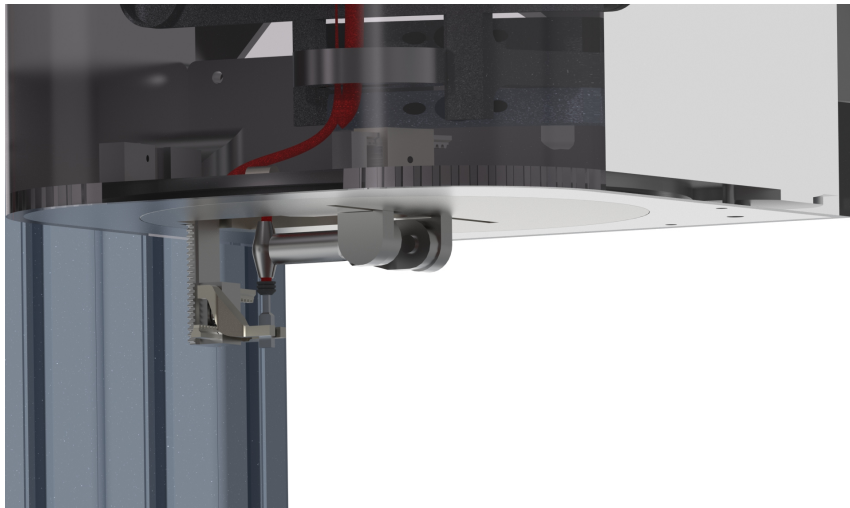


Figure 5.12: Routing tool comes up to grasp the wire end

Once it is secure, the terminal gripper releases the terminal and opens, allowing the gripped wire end to be rotated down 90 degrees, with the routing tool swinging down between the terminal gripper tool (see Figure 5.13). While the terminal gripper is retracted back into the tool head, the tool head is lowered and the routing tool is aligned with the appropriate cavity of the housing (see Figure 5.13). The tool head is then moved so that the terminal is inserted into the connector cavity (see Figure 5.13).

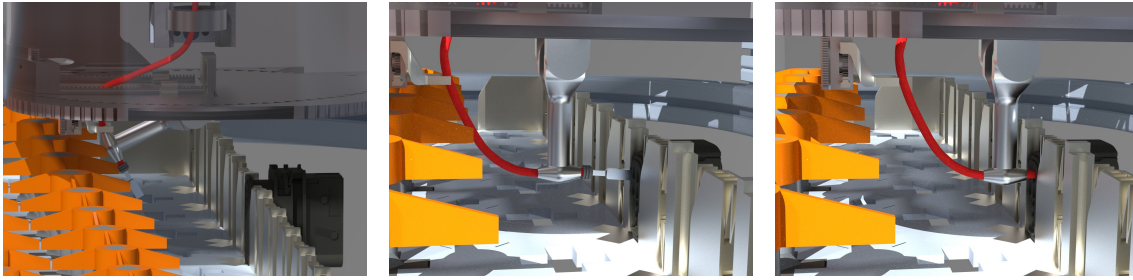


Figure 5.13: The routing tool rotates down and inserts the wire into the connector housing cavity

When the terminal is fully inserted and the terminal is locked in place, the routing tool somewhat releases the wire and begins routing the wire outwards between the routing pins (E) (see Figure 5.14). The routing tool is equipped with two slots on the inside of each half, which assists in the centring of the wire during this stage. The entire tool head moves along the routing board and between the flexible flaps on top of the routing pins. The pins are spaced 60 mm in a grid across the board. The manufacturing file determines the path of the routing, with a yet-to-be developed path-planning program to obtain the optimal path.

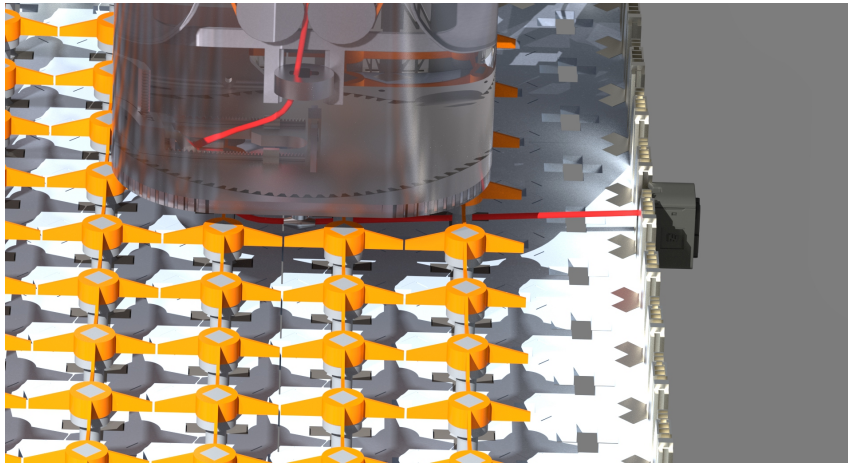


Figure 5.14: The tool head starts routing the terminated wire between the flexible pins

Once the routing is completed and the second housing is close to being reached, the terminal on the other end of the wire also needs to be aligned. The terminal gripper assists with this by gripping the wire prior to the terminal leaving the belt feeder. While the belt feeds the wire, the terminal gripper with the gripped wire is lowered until the belt feeder is cleared (see Figure 5.15). The rotational gripper of the visual terminal alignment system grasps the wire, and the terminal gripper releases it. The visual aligner system now aligns the second terminal with the help of the upper sensor. The terminal gripper now grasps the aligned wire and the rotational gripper releases the terminal. This process is illustrated in Figure 5.16.

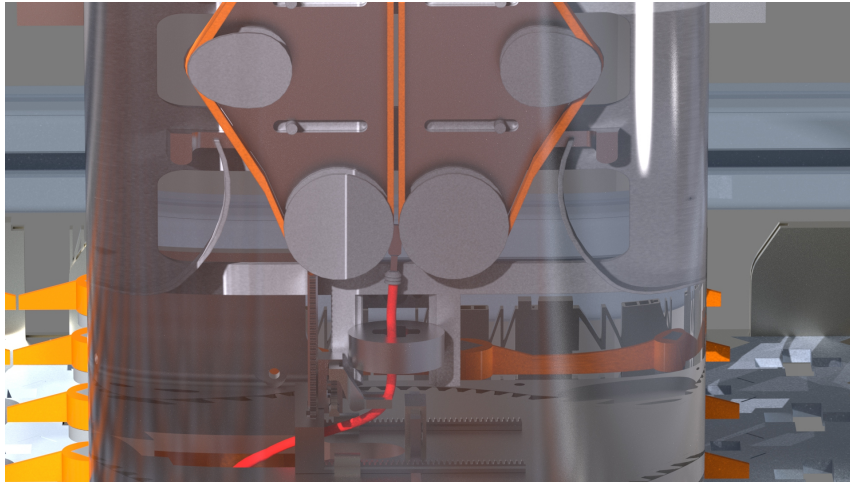


Figure 5.15: The terminal gripper assists with positioning the second wire end for alignment

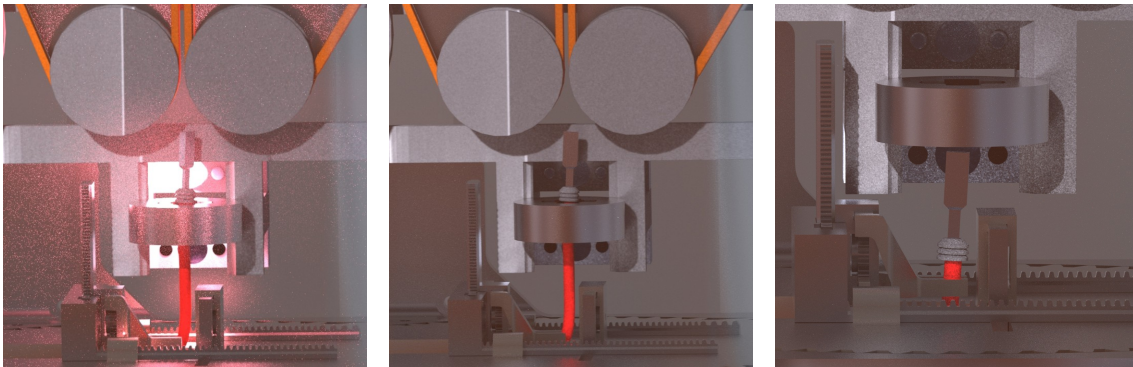


Figure 5.16: The terminal on the second wire end is aligned and moved down

Meanwhile, the routing of the wire continues in synchronisation with this process. The terminal gripper moves the second wire end down and outward, and the routing gripper is rotated upward to grip the second wire end. Once it is gripped, the terminal gripper disengages the wire, and the routing gripper moves down, similarly to the first wire end (see Figure 5.17). The terminal is then aligned with the cavity of the second housing and inserted.

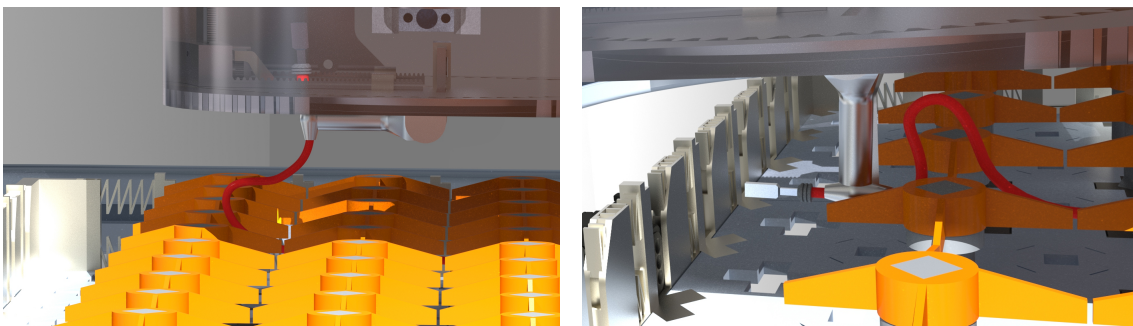


Figure 5.17: The routing tool is moved down with the second terminal and wire end

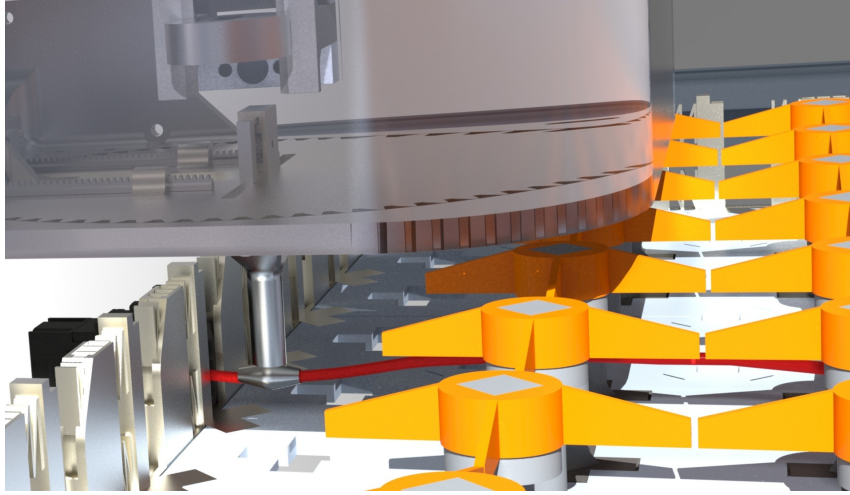


Figure 5.18: The terminal is inserted

The routing gripper disengages and the tool head moves back to the retrieval position, ready to retrieve the next wire. The entire routing process of a wire happens very quickly, with multiple concurrent processes like connector handling, routing and wire preparation, as described above.

5.3 Features of the Proposed Solution

The proposed solution demonstrates a cost-effective concept, with an expandable design. The assembly board is modular and expandable, with $180\text{ mm} \times 180\text{ mm}$ sections that can be assembled to form custom sized boards. This is beneficial if a certain instance of the system is only used to produce similarly sized harnesses. The housing holders are modular and assembled in the same way.

The tool head does provide some custom-manufactured parts, the gantry and rail system are modular, designed around the 40-series v-slot system. Thus, the expandable part of the system uses low-cost, commonly available parts.

The storage system is likewise modular, with the stacks being vertically and horizontally expandable. Due to the limited reach of the connector grasping arm, only two stacks would be reasonable vertically, however horizontal expansion is virtually infinitely expandable, as the v-slot that the connector transport system can be expanded with the storage system.

5.4 Simplifications of the Proposed Solution

As stated in Section 1.2, the aim of the thesis is to produce a high-level geometrical model of the proposed solution. Thus, the CAD model of the proposed solution lacks components such as motors and belts and only includes the basic axes of movements. Further, the dimensioning is approximate, especially for clearances and tolerances. Dimensions would need to be iteratively determined. Other details such as screws, gears, springs, and brackets are either simplified or not included.

Simplifications have also been made with adjacent systems. The connector storage system is represented by a simple CAD model of the proposed solution, but the plugged connector housings need to be added from central storage to these compartments in some way as well. This could be a manual process or a conveyor belt, but this integration will be dependent on the preconditions of the manufacturing site. Additionally, the wire preparation system is depicted as a simple black box as the geometry and way of outputting varies depending on the machine model.

Traditionally, the assembly board is set up vertically to make it easier for humans to work. In the proposed solution, however, the assembly board is configured horizontally, as modelled in CAD. This is a simplification rather than a strict design choice, and the solution allows for it to be changed if needed. The main advantage of a horizontal setup is that gravity does not restrict harness placement on the board. The trade-off is that harness removal becomes more difficult if it were to be manually done. With a vertical setup, the harness rests on the pins, requiring them to be strong enough to support its weight. These considerations must be addressed in further detailed design.

5.5 Manufacturing Capability with Respect to Variant Variety

In Section 1.5, it was stated that the proposed solution would be evaluated with a harness variant family. A side radar harness was selected for its relative simplicity, after suggestions from the interviews with wiring engineers, outlined in Section 3.4.1. This harness family includes several variants; the two with the shortest and longest branch lengths were selected for this study. Figure 5.19 shows one of these variants, while Figure 5.20 shows the other.

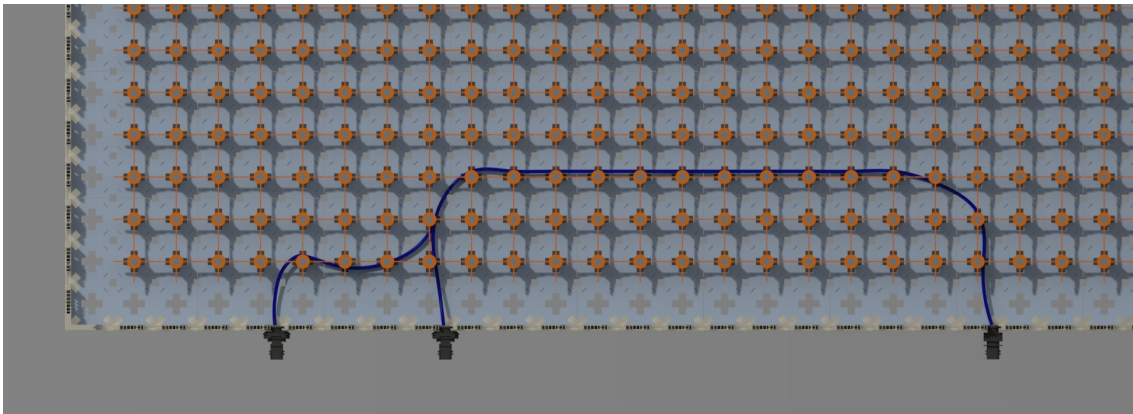


Figure 5.19: Shortest variant of radar harness

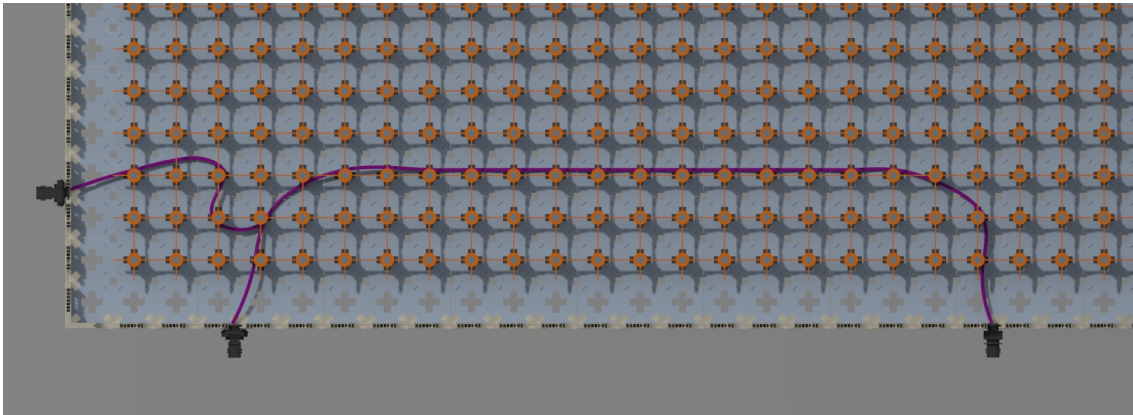


Figure 5.20: Longest variant of radar harness

Note that the harness is simplified to one cable, instead of showing every included wire. Additionally, the connectors are not the same as in the official drawing, as the currently used connectors lack the features that this prototype interacts with. Thus, all connectors in the simulated harness are HDSCS-connectors.

In addition, a simple harness comprised of two wires and two connectors was manually routed along the scaled-down version of an assembly board. This tested the routing pins and connector holders with end-to-end routing of a harness. The wires performed stiffer than expected, something that needs to be considered if a similar system is to be developed further (see Figure 5.21).

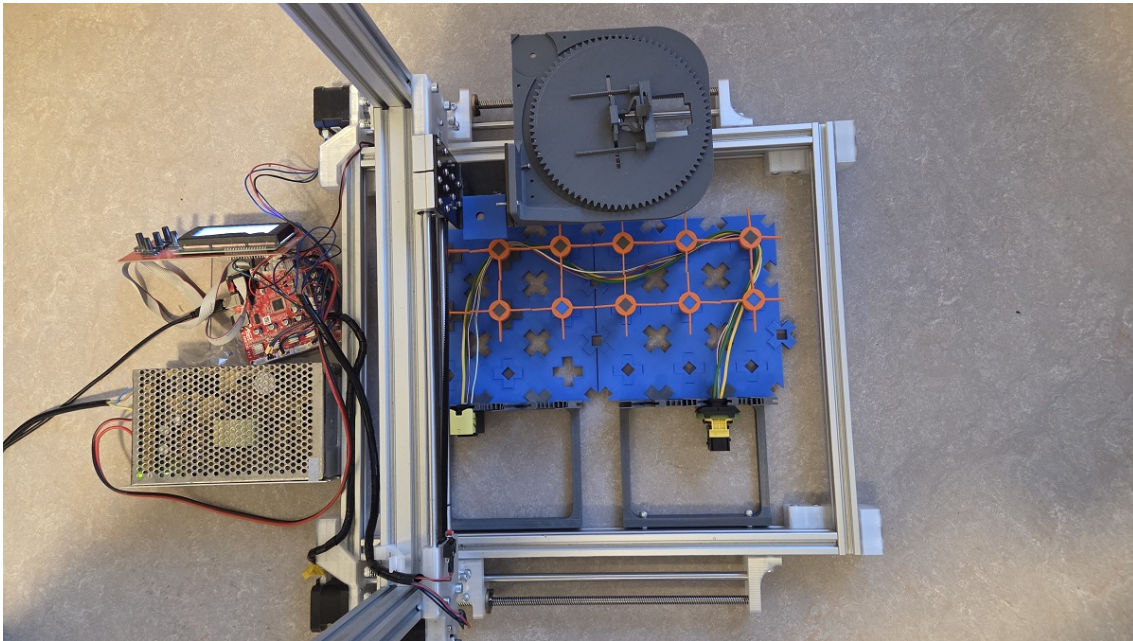


Figure 5.21: Manually routed test harness

Having established the technical feasibility of the proposed solution, the next chapter broadens the evaluation beyond purely technical aspects to also consider manufacturing, design, economic, ethical, and environmental impacts.

6

Impact Assessment

This chapter assesses the broader implications of the proposed solution across four dimensions: impact on manufacturing, influence on wiring harness and component design, economic implications of implementation, and ethical and environmental impacts of deployment.

6.1 Impact on Manufacturing

This section assesses how the proposed solution affects the manufacturing of harnesses. It includes the immediate impact on the manufacturing process, the potential benefits of further automation, and how the role and responsibilities of wiring engineers may evolve as a result.

6.1.1 Impact on the Wiring Harness Manufacturing Process

Automation of the selected operations with the proposed solution would have a significant impact on the routing operations carried out during manufacturing. The placement of housings on the assembly table, the routing of prepared wires and insertion of wire ends into housings are now automated. This saves significant manual labour, as one operator could monitor several systems at once. Among these activities are clearing the assembly board when the harness is finished, stocking of connector storage (if not further automated), and handling of any errors and mishaps. Automation is expected to increase productivity, which would lead to operators only doing process steps including in and after *Adding Wrappings*. In such a scenario, no significant changes in workforce is expected at the manufacturing site, as increased productivity increases the labour required for the remaining manual steps. The implementation of the system would increase the output of harnesses at the specific manufacturing site. Product quality is likely to increase as automated processes produce more repeatable results than manual manufacturing. Further, traceability would be improved, as wire rolls and connector batches used in specific harnesses could automatically be logged in a complementary harness-specific digital twin file. This would be beneficial for tracing deviating batches, or any unexpected occurrences throughout the harness lifetime.

Since no comparable system exists, productivity improvements cannot be reliably estimated using empirical data. However, a rough estimation can be made based on previously automated operations within the wiring harness manufacturing process. For example, cutting and stripping wires manually produces 120 to 200 wires per hour, whereas automatic processing is capable of producing 500 to 800 wires per hour. Meanwhile, terminal crimping can be performed at around 80 to 120 crimps

per hour by a human worker, while a machine can perform between 400 and 600 crimps (Hooaha Harness, n.d.). This means that automated cutting and stripping is around 400 % as efficient as manual processing and automated crimping of terminals is around 500 % as efficient as the manual counterpart. Thus, it is reasonable to conclude that automated routing and termination can achieve similar productivity improvements. Equation 6.1 approximates the manufacturing time for a certain part of the process after automation (t_a) based on the relative productivity of the automated process compared to the replaced manual process (R_p) and the time for the replaced manual process (t_m).

$$t_a = \frac{t_m}{R_p} \quad (6.1)$$

Further, the new manufacturing time ($t_{new,tot}$) can be calculated by adding the manufacturing time for the automated process (t_a) to the manufacturing process time of the non-affected operations (t_{rm}), as presented in Equation 6.2.

$$t_{new,tot} = t_a + t_{rm} \quad (6.2)$$

Current process times for the affected process operations could be obtained for two harnesses, one chassis harness and one cab harness. For the provided chassis harness, 13 % of the total harness manufacturing time directly involves those operations that have been automated, the operations within *Wiring Operations*. For the provided cab harness, 29 % of the total manufacturing time involves the automated operations, due to the reduced amount of wrappings. Due to data confidentiality and simplification, the total manufacturing time will be assumed to be 100 minutes, thus resulting in wiring operations that currently take 13 and 29 minutes, respectively. Assuming a relative productivity of 400 %, the manufacturing time for wiring operations after automation (t_a) become 3.25 and 7.25 minutes, respectively. Again, assuming that both harnesses took 100 minutes to produce manually, the new manufacturing times of 90.25 and 78.25 minutes are obtained, respectively. Converting back to percentage, this means that a time reduction of 9.75 % was achieved for the chassis harness production, while the cab harness would be produced 21.75 % faster if routing and terminating were to be automated.

Additionally, further time would be saved upon automation, as the traditional human-operated assembly boards would not be needed. Thus, time would be saved as the one-time operations in *Setup* such as tooling changes would become obsolete. Depending on implementation and the new quality enforcement process, this could significantly shorten PCR introduction times, as procurement, installation and verification of new tooling would not be required. Additionally, the proposed solution's software would handle the re-configuration of the routing automatically from the X2ML or other design file.

A downside of automating the routing in this way, is that implementation of the proposed solution would actually make *Adding Wrappings*, *Adding Adapters* and *Taping*, *Marking* less efficient for humans, as the tight spacing between the routing pins would make wrapping more difficult. Additionally, the wrapping process also

requires instructions for lengths, positions and part numbers. With universal assembly boards, such information would likely need to be projected or displayed on a screen, and the assembly board part of the solution would need to be moved from the solution entirely, as the board would need to be angled for ergonomic work. Such a scenario would not be feasible, as the system is designed for automation and not for manual assembly. Thus, if the solution is implemented as-is, additional development of an assembly board moving system would need to be developed, and an assembly board with a complete routed harness would need to be replaced by an empty board, so that the solution can start routing the next harness, minimising downtime. Implementation of the solution as-is would thus not be feasible from a manufacturing point of view. Therefore, it might be more interesting to investigate what impact a further developed solution would have, where *Adding Wrappings*, *Adding Adapters* and *Taping, Marking* are also automated.

6.1.2 Manufacturing Impact of Further Automation

In practical terms, tape wrapping and sleeving with DLPS or corrugated tube would need to be done on the same assembly table to reduce the time to move the harness, during which no value-adding progress is being done on the harness. Likely, this would mean adding a second tool head to the X-axis gantry of the solution, that could handle bundling and wrapping. Addition of adapters would likely be left out even in a further developed solution, as this step is deemed the most complex due to the variation of shapes, sizes and mounting techniques. Though, for the purpose of this exercise, it would still be interesting to investigate the effects of full automation, excluding testing, inspection and packaging.

Automating to the extent described above would translate to about 95 % of the current total time, based on actual timing data on operation durations obtained from the company. Using Equation 6.1 and 6.2, and continuing to assume a productivity of 400 %, a much more significant 71.25 % reduction in manufacturing time would be achieved.

Such a situation would open up further possibilities. As presented in Section 3.2.5, Navas-Reascos et al. (2023) found that a high degree of automation would be more profitable in high-wage countries than low-wage countries. This is because the wages change more depending on the region while the operation cost of the machine remains relatively stable. Near-full automation of harness manufacturing would thus make it more feasible to move harness production closer to, or even under the same roof as the final truck manufacturing site, which is mostly in high-wage countries such as Sweden and Belgium. This would lead to significant reductions in transportation lead time and logistics costs (Lorenz and Mayer, 2023), and together with reduced design-to-production lead times, it would make it possible to adapt an Agile methodology with significantly faster feedback loops between truck production and harness redesign where necessary. For example, small adjustments in lengths and tape marking positions that are noted during the installation of harnesses into the truck could be made within days, instead of weeks or months. This change would also be in line with lean production, eliminating the waste of old tooling. It would

also help reduce the waste of deviating harnesses, as assembly operator feedback could directly lead to adjustments for the next harness if just-in-time production, synchronised with the truck production is implemented. This would eliminate a scenario where an entire batch of deviating harnesses are manufactured, that then need to be discarded.

Such changes would have company-wide implications, and would especially impact the engineers that design the wiring harnesses.

6.1.3 Potential Changes in Demands and Responsibilities for Wiring Engineers

A more automated harness manufacturing process would likely lead to a reduction in degrees of separation between the wiring engineer and the manufacturing process. Potentially, this could even be reduced to zero degrees of separation, with engineers being the last person in the chain before the harness is manufactured, similar to 3D printing. This would also shift part of the responsibility for quality to the wiring engineers. The technicians that operate and supervise the machine and the supplier would still be responsible for the quality of the production process, but much of the quality of the final product would be transferred to the wiring engineers. It would also entail that wiring engineers would need to be more knowledgeable about and aware of limitations of the manufacturing process, as they would be responsible for the entire process, from design to finished product.

The Agile processes that are used today could be taken advantage of more than currently, with current lead times being much longer than a single sprint. Innovation in the production process could shorten these lead times drastically, as harness iterations could even be produced daily, meaning test-fitting into trucks and potential redesigns of the harness could be done faster and more flexibly. This would encourage a TDB (test-design-build) way of working as opposed to today's methodology, where a design needs to be formally finalised before being sent to the supplier, entering production weeks or months later.

This change in the way of working would certainly increase the need for wiring engineers to interact with the production process and produced harnesses and if the harness production is moved close-by to the final truck assembly site, closer contact with the production site would be needed to maximise the benefits. Potentially, some wiring engineers could even reside at the production site, especially during periods with frequent iterations. This change in the way of working would likely further increase the engineers' practical knowledge of the product.

With this change, the day-to-day tasks of wiring engineers would see a reduction in communication with supplier engineers, an increase in communication with the manufacturing site and even closer product contact than currently. The workflow of designing harnesses would likely change, and the wiring harness itself would also need to change in multiple ways.

6.2 Impact on Wiring Harness and Component Design

The resulting solution is capable of manufacturing harnesses with non-twisted signal wires and the HDSCS connectors that were defined as a requirement. Twisted wires are currently required for CAN-signal wires to reduce signal interference. Automated production systems already exist that are capable of twisting wires, but the routing would need to be adapted so that CAN-signal wires can also be routed, as this is a limitation of the current proposed solution that expects one terminal and wire end per prepared length. Another limitation is the non-compatibility with splices. The proposed system is only capable of handling continuous wires, so any splices mid-way along a wire could not be handled by the proposed solution. Thus, the functionality of splices would need to be transferred to alternative solutions such as internal connections in connectors, shorter jumper cables, or be handled by the ECUs through internal connections.

Currently, only certain HDSCS connectors can be mounted in the connector holders of the solutions, as they have similarly dimensioned backshell mounting lips. Some other HDSCS connectors also have this feature, but either deviate too much in dimension or are completely round, making rotational fixation unfeasible. It is unclear whether this variation in the lip dimensions and shapes serves a higher purpose, like preventing incorrect assembly or installation through geometry, but features used as references and for manipulation would nonetheless need to be standardised - this is yet another example where the needs for manual and automated assembly differ.

Further, using the backshell mounting lip would not make possible the automated mounting of backshells, thus a redesign of all connectors used for the harness, beyond HDSCS, would need to be needed to introduce a common locator feature on all housings that is placed behind the backshell lip. This could be a square protrusion, a slot, or any other geometric feature that is capable of being used both for handling and mounting. The variation in sizes and connector cavity positions in relation to the locator would be programmed into the system, so the machine can account for these both during retrieval from storage, mounting in the updated connector holders and during wire termination. If the locator is symmetrically placed, it could also open up other possible connector storage solutions, such as conveyor belts with spaced interfaces, which would standardise the storage across connector sizes and families. If the locator is sufficiently small, the connector holder at the assembly board perimeter could likewise be small, and be placed more frequently along the perimeter, increasing the flexibility of harness design.

As a consequence, some connector terminal types may be phased out, as the addition of the locator would require significant product changes and result in added costs at the connector manufacturer, leading to more economically viable options if the change only involves select connector families. This could also entail a reduction in the number of used terminal variants, further standardising the design of harnesses.

Due to the termination of wires before wrapping, wrapping will have to be made with slotted protection or tape, instead of non-slotted tubular wrappings. Traditional

DLPS sleeves and corrugated tube will have to be changed for slotted, zipped or two-part variants. This, however, will not be handled by the proposed solution.

6.3 Economic and Cost Impact of Implementation

An economic impact assessment was conducted to investigate whether the implementation of automation with the proposed system would be financially viable. The impact assessment not only shows if the automation is viable or not, but also includes approximated costs to develop the system, to provide a holistic picture of the effects over time. The economic impact was structured as follows. During years 1 to 5, the development of the necessary hardware and software is planned, as shown in Table 6.1. The timeline has a low level of detail as more work needs to be done before the exact times for each phase can be determined.

Table 6.1: Approximate timings of project phases

Phase name	Year
Project planning	Year 1
Hardware and firmware development (50 % developed)	Year 2
Remaining hardware and firmware development, X2ML conversion software development	Year 3
Prototype refinement and testing	Year 4
Further testing, integration, commissioning, and training	Year 5
Rollout of system fleet	Year 6+

6.3.1 Implementation of NPV Equation

As presented in Section 2.6, a calculation of the Net Present Value (NPV) was used to measure whether automation of the selected operations would be a net economic benefit, compared to current manual manufacturing. The benefit of an NPV calculation is that it gives a more detailed answer than a simple cost-benefit calculation as it takes into account the discount rate and visualises the net value over time, showing the break-even point of returns. This implementation of the model includes annual savings, added annual costs and initial investment costs.

Within the savings, factors such as costs for manual labour, tooling changes and engineering costs to implement the changes have been included. The added annual costs include machine and installation costs for the applicable years, servicing costs and running costs such as operator and electricity costs. The machine costs vary over time, according to the diffusion equation, Equation 2.2 presented in Section 2.6. The service costs vary in reality, but are simplified to be a constant value, multiplied by the number of machines in the fleet. The investment costs include hypothetical costs

for developing the solution. This calculation presumed an in-house development for simplification, although in practice it would be expected to be outsourced or completely handled by a wiring harness manufacturing company. These development costs were also sequenced in various development phases, over a 1 to 5 year period. Thus, the NPV method started at the 6th year from the start of development.

Additionally, it is worth noting that due to several figures such as wages, tooling costs and company-specific discount rates being confidential, these values are not shown. Values that could not be found were approximated by the appropriate experts in the company. Consequently, due to these values being used, the resulting values will not be shown either. However, the plot that these values produced without the actual values, along with the change over time, will be presented. Values for the engineering hours needed for developing and implementing the proposed solution were estimated by an AI model, where it was prompted to provide this information for a generic manufacturing system, not detailing the proposed solution. The values for the different development phases were multiplied by the average hourly wage for an engineer.

The NPV equation was used in combination with the equation for the diffusion model, to simulate the successive implementation of the solution at manufacturing sites. The calculation used the values that follow: the solution is expected to increase productivity to 400 % for approximately 20 % of the current manufacturing process, time-wise. This estimate of 20 % is based on the current timings for the affected operations for the chassis and cab harness examples, which were 13 % and 29 %, respectively. In practical terms, one machine could replace four workers for the selected operations. It is approximated that one person could monitor and operate six machines, thus $1/6$ of the hourly wage will be added per machine. Additionally, approximated electricity costs and servicing costs were added. The diffusion or rollout rate k was set at 0.8, and the inflection point (year for fastest diffusion, t_0) was set at 3, for a realistic rollout speed.

In addition to analysing the effects of automating 20 % of the current manufacturing duration, a 95 % automation grade, described in Section 6.1.2 was also considered. Such a scenario would entail much greater savings in labour costs, but would also require the development of an additional complex multi-material wrapping system. For simplification, it is assumed that all development and machine costs are doubled in the 95 % scenario compared to the 20 % scenario.

6.3.2 Economic Impact of the Two Automation Scenarios

The resulting impact analysis can be seen in Figure 6.1, with the blue trend line showing the net present value of the 20 % scenario, while the yellow line represents the 95 % scenario. A significant difference can be observed, both in the break-even period and in the amplitude of the curves. This is mainly due to a higher extent of automation, leading to both a larger number of solutions in the fleet, and also more capable solutions requiring automatic wrapping systems among others, reflected in the doubled machine cost. Thus, near-full automation of harness manufacturing becomes a significant up-front investment. On the flip side, the returns are also

greater, and the net present value of the 95 % automation scenario is approximately two times higher at year 20 compared with 20 % automation, and is expected to grow at a faster rate beyond 20 years.

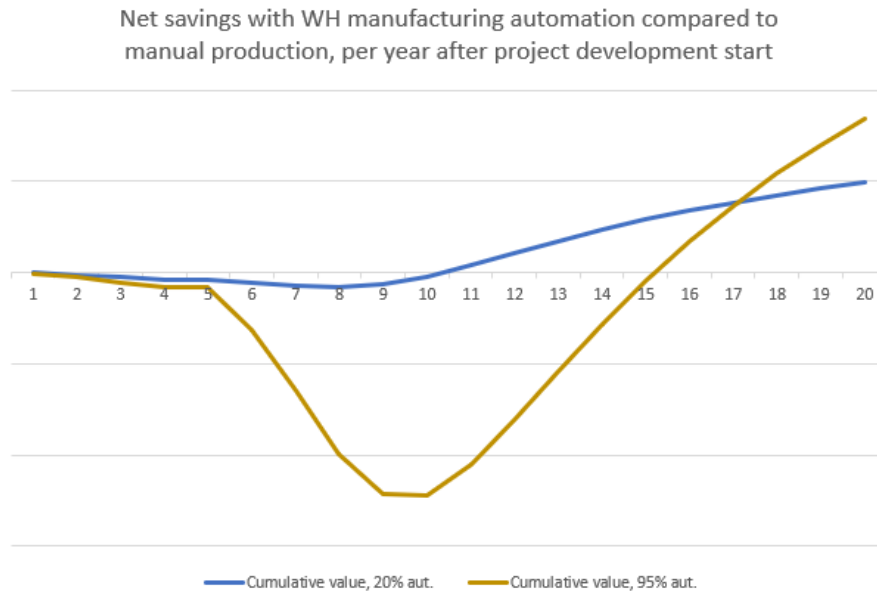


Figure 6.1: NPV comparison of the two automation levels

Additionally, near-full automation at 95 % would make it viable to move production to be in conjunction with the truck manufacturing site. This would essentially reduce logistics costs to zero, and would also result in packaging costs being drastically reduced, as harnesses would not be packaged for shipping. However, logistics cost savings are difficult to estimate. Other affected, but not easily quantifiable factors such as the cost of PCR introduction delays and any knock-on effects to other departments further point to even greater savings than those already presented.

6.4 Ethical and Environmental Impacts of Implementation

The implementation of an automated wiring harness manufacturing machine has several ethical and environmental implications. These areas include workforce dynamics, societal impacts, and ecological considerations, all of which are discussed below.

6.4.1 Workforce Impacts

At the manufacturing site where the solution is implemented, throughput would increase without a significant change in the number of manual workers. Existing workers would be reassigned to other tasks, such as wrapping operations, rather than being replaced. In addition, new and more qualified jobs would emerge, including machine operators, maintenance technicians, software developers, and R&D personnel with specialised knowledge of the automated system.

However, the ability to produce more harnesses does not imply a proportional increase in market demand. If the production capacity significantly exceeds demand, other factories within the manufacturing network may face reduced orders or closure. This could lead to job losses elsewhere, even if the factory implementing the automation retains its workforce. The net impact on employment therefore depends not only on local automation but also on broader market dynamics.

If adding wrappings was automated alongside wiring operations, approximately 95 % of the total manufacturing time would be automated. Based on the estimated throughput increase of 400 % for the automated operations and the assumption that a single operator can run up to six machines, the required workforce for the automated operations could be reduced from 24 workers to 1 operator for every 6 machines, corresponding to approximately a 96 % workforce reduction. While new jobs would be created in software, maintenance, and R&D, the net number of manual labour would decrease significantly, meaning that many workers would lose their jobs.

6.4.2 Societal Impacts

The wiring harness industry has long been regarded as difficult to automate due to the flexible nature of DLOs and the high product variety. A successful implementation of automation in this sector could therefore serve as a reference case for other industries facing similar challenges. Demonstrating that such automation is feasible and brings substantial benefits, such as improved quality, reduced lead times, and lower costs, may encourage broader adoption of automation across other manufacturing domains. This could accelerate the transformation of industries that have traditionally relied on manual labour, potentially leading to widespread productivity gains and economic growth.

Yet the transition is not geographically neutral. Manual labour reductions will likely concentrate in low-wage manufacturing regions, while new technology roles will emerge in high-wage countries. This could lead to a further divergence in economic opportunities between these regions.

6.4.3 Environmental and Ecological Impacts

The implementation of an automated wiring harness manufacturing machine presents both environmental costs and benefits. The production of the machine requires raw materials, including metals, plastics, and electronic components, each with its own extraction and manufacturing footprint. In addition, the machine consumes electrical energy during its lifespan, contributing to greenhouse gas emissions.

On the positive side, automation reduces material waste by minimising routing errors, incorrect wire lengths, and faulty crimps. This lowers the consumption of raw materials and the energy needed for replacement components. Furthermore, by making local production economically viable, automation can shorten supply chains and reduce transport emissions, as harness production is currently often outsourced to low-wage countries (Lorenz and Mayer, 2023).

While the machine's production and operation carry a definite environmental cost, the long-term benefits of reduced waste and shorter logistics are likely to outweigh these burdens, resulting in a net positive environmental impact over the machine's lifetime.

6.4.4 Balancing Benefits and Burdens

In summary, the automation of wiring harness manufacturing presents a complex interplay of ethical and environmental considerations. Workforce restructuring and potential job displacement are legitimate concerns, balanced by the emergence of new technical roles in software, maintenance, and R&D. The societal influence of demonstrating automation feasibility could accelerate broader industrial transformation. Environmentally, while the machine's material and energy footprint must be considered, the benefits of reduced waste and shorter logistics likely outweigh these costs.

7

Discussion

In this chapter, the fulfilment of objectives, requirements and desires will be discussed. The research questions that the thesis is based on will be revisited and answered. The use and application of the methods will be discussed, and both the proposed solution and the thesis as a whole will be reflected upon.

7.1 Answering the Research Questions

Below, the research questions will be revisited and an evaluation will take place whether or not the research questions have been answered and how. As a reminder, the research questions are as follows:

- *Research Question 1:* What are the challenges associated with automating wiring harness manufacturing and how can they be overcome?
- *Research Question 2:* How could the overall architecture of a solution that automates the manufacturing or part of the manufacturing look like and how would such a solution function?
- *Research Question 3:* What impact would full or partial automation of wiring harness manufacturing have on the overall truck and harness manufacturing process, harness product design, and on the economics of the company where it is implemented?

Research question 1 was answered in Section 3.6.1, Table 3.2. The main challenge was found to mainly be the product, both the flexible nature of wires, classified as DLOs, and the high variety of parts and components. It was also found that currently no strong incentive for automation exists due to offshoring of manufacturing to low-wage countries. Additionally, current attempts at automation either try to replace humans with robotic arms in a one-to-one substitution, or the solutions do not facilitate automation of all operations, like adding wrappings. Solutions for these were presented, which provided recommendations for the product development phase of the thesis.

Research question 2 was answered in Chapter 5. The solution proposal includes a Cartesian CNC-like movement system, that is capable of routing individual wires on a universal assembly board. The assembly board features holders along the perimeter that are used to fix the connectors, which are placed out with a transportation system that retrieves them from a storage system.

Research question 3 was answered in Chapter 6. The proposed solution would lead to savings long-term, however manufacturing-wise it would not make sense to only automate to just the extent of the thesis scope, as manual labour would still remain for most of the manufacturing process. The product would need to change in several ways, the functionality of splices would need to be transferred to internal connections in connectors or ECUs, and connectors would need to be complemented with a standardised interface for manipulating these in an automated way. Near-full automation of 95 % would economically be the most beneficial long-term, although partial automation of 20 % would require much lower up-front investment.

7.2 Fulfilment of Requirements and Desires

The requirements and desires presented in the Requirement Specification should be fulfilled by the proposed solution. In this section, it will be evaluated whether this actually has been achieved. Due the proposed solution still being at a concept phase and as a full-scale functioning prototype hasn't been constructed yet, certain requirements may be difficult to evaluate against. However, it can be determined if the solution fulfils the requirements in theory. A review of the requirements and desires follow.

Requirements 1.1 and 1.2 are mostly fulfilled, as the solution can produce a harness from signal wires, and according to the design file, as explained in Chapter 5. However, it is important to note that although all current harnesses should theoretically be able to be routed, but all current connectors can't be used as no common reference, grasping and securing feature was found among all used families. Further, the routing of harnesses needs to be simulated for all harnesses, to be certain. Desire 1.3 is not entirely fulfilled, as the solution is not capable of routing twisted wires in its current form. Thus, human labour is needed for this task. Desire 1.4 is however fulfilled, as the assembly board is universal and harness-neutral. The architecture of the solution makes it possible to add passives to the routed harness if the solution is further developed. If adding wrappings is done manually, it would be more difficult than the current manufacturing method, thus fulfilment of desire 1.5 is conditional.

Revisiting the resulting productivity improvements, the solution could save 9.75 % and 21.75 % of the total manufacturing time for the two analysed harnesses. Thus, fulfilment of desire 2.1 depends on the harness. The primary objective of the thesis was "to reduce the current wiring harness manufacturing cost by 15 % by developing a manufacturing machine that automates select steps of the manufacturing process". The fulfilment of this objective can not directly be evaluated with the NPV result, as that saving is measured over time and the relative savings increase over time. However, disregarding machine costs and development costs and only comparing direct running costs, the proposed solution would contribute to approximately a 13 % saving per year, even though making such a simplification does not make sense. Including these investments, additional machine costs, costs for integration, as well as costs for handling the incompatibilities and complexities of the solution, savings would likely reduce further. Additionally, even if manufacturing cost is largely made up of labour costs, factors such as part and material costs, overhead

costs and margins do not change significantly, further reducing the percentage of savings. Thus, desire 2.2, and with it the main objective of the thesis, was not fulfilled. Requirement 2.3 can not be evaluated against due to still being in the concept phase, however the solution and subsystems include the technology and components required to achieve the needed tolerances. For example, Cartesian CNC systems are often used for FDM 3D-printing that requires even finer tolerances than what is required to perform the operations being done by the proposed solution. A PFMEA study (Appendix C) found that the proposed solution would achieve an RPN score of 78, which is lower than the maximum limit of 265, fulfilling requirement 2.4.

The wire gauges that are specified in requirement 3.1 are compatible dimension-wise. The flexibility of the thickest specified wire may be limiting in some places, like during the horizontal movement of the terminal gripper, but issues like this can only truly be seen after a prototype is constructed. If this were to become a problem, increasing spacing and changing of dimensions would solve any potential geometry-related problems. The same can be said for requirements 3.2, 3.3 and 3.4. Desire 3.5 regarding multiple wire colours falls on the wire preparation machine, thus the proposed solution would not inhibit this desire. Desire 3.6 about maximum wire length should also be fulfilled, as long as the wire preparation machine can produce such long wires. If further testing of long wires results in any complications, a feature handling this needs to be added. Desire 3.7 about handling up to 122 connectors is not fulfilled by the CAD model of the solution, but due to its modularity, expansion of the board could facilitate this. The routing pins have a rectangular space of 40 mm by 50 mm between them, making it just about possible to route a 50 mm diameter harness. Additionally, the space between the flaps is 1 mm, which is smaller than the smallest compatible wire, that is 3 mm in diameter. Thus, requirement 3.8 is fulfilled. Requirement 3.9 regarding handling of MCP 1.5 and 2.8 terminals is possible due to the visual terminal aligner system. And the selected connector housings can be stored, transported and inserted into the connector holders, fulfilling requirement 3.10.

Regarding the safety requirements, category 4, the proposed solution is still in an early phase, and is not detailed enough to evaluate against these requirements. The same is true for the quality requirements, category 5, although the quality is expected to increase upon automation.

Requirement 6.1 regarding integration with the remaining manufacturing process is fulfilled if the wrappings are to be added in an automated way, however it is not adapted to manual operation. Thus, the fulfilment of this requirement is also conditional.

Within the sustainability requirements, 7.1 regarding reduction of material waste is expected to be fulfilled, but once again requires a functional prototype to evaluate. The solution is designed with 40-series v-slot profiles and modular components, making maintenance and repair favourable, fulfilling desire 7.2. Desire 7.3 is not fulfilled, as some custom-manufactured parts are used in the tool head.

The solution is expected to function in the environment defined in requirements 8.1 and 8.2, and is not expected to have any hot surfaces or generate a substantial sound level, fulfilling desire 8.3 and requirement 8.4.

All in all, most requirements and desires can be considered fulfilled, although several of these can only be evaluated with a fully capable prototype of the solution.

7.3 Application of Methods

The product development approach within the master thesis was largely based on the *Product Design and Development* framework by Ulrich & Eppinger, although with some modifications to the methods, when needed. The thesis started with defining the scope. Then, a qualitative analysis was performed of the stakeholders' needs, which, combined with a literature study of the academic and industrial fields, provided the data needed to create the requirement specification. Methods such as function trees and process DSMs helped to structure functionality and further reduce the scope. Diverging methods such as Braindrawing and morphological matrices were used for idea generation, before the solution space was reduced, with the help of converging methods including elimination matrix and Pugh matrix. In addition, 3D printing enabled iterative prototyping and testing, complementing the theoretical methods with experimental data. Below, each of the methods will be discussed in further detail.

The literature study was mainly performed with the use of Google Scholar, with a structured approach, where the read articles were classified both according to relevance and theme. The literature was searched for challenges with current manufacturing methods, potential solutions, recommendations and conclusions. Additionally, the literature was used to gain a deeper understanding of the subject as a whole. This process was both conducted with an open mindset, but was on the other hand often done critically as well.

For example, many solutions implemented a one-to-one replacement of a human with a robot arm. This was thought to be the wrong road, as humans and robots are good at very different things. Many attempts of using robot arms were found in the literature, while at the same time no such commercial solutions existed. This led us to pivot away from such solutions and instead resulted in a Cartesian CNC-system as the best subsystem alternative, as these types of motion systems are successful in both 3D printing and pick-and-place machines for making circuit boards. Several articles were also found that later became useful for the impact analysis.

Throughout the literature study, it also became evident that the handling of wires and DLOs in general needs to be conducted with total control. Once the wire or wire end is released, it will most likely deform, and thus needs to be identified before control of it can be regained again. This requires both sensors and an algorithm, which could at best achieve a 90% success rate per the literature, which is far too low for a commercial machine. Thus, it was determined that control needs to be retained of the wire at all times, so that the position of wires can be known without complex visual systems. This in turn led to the design guideline that wires need to

be completely routed and terminated, from connector to connector, before they are released.

The interviews were useful for getting to know the various perspectives and needs of the different stakeholders. Initially, the eventual driving factors behind automation were thought to be high manufacturing cost, long lead times and quality issues, however the interviews only confirmed the first two, with the third being a non-issue. Initially, quality was thought to be an issue as the manufacturing site sometimes experiences issues like too short or too long branch lengths, but during the interviews it became evident that this was due to incorrect design, which is not the supplier's fault. The interviews were also used for confirming correct understanding of the manufacturing process, with a printed process diagram brought to many of the interviews, which the subjects could comment on.

Engineers at the harness supplier were also asked, several times, if they would be open for an interview, but these never happened, except for a short, unstructured discussion. This was unfortunate, as they would have been able to provide the most reliable information to support the thesis. Additionally, it would have been beneficial to have been able to visit one of the supplier's manufacturing site, even though these are located outside the country. As a substitution, Quokka's LinQ site was visited, where smaller, prototype-intended harnesses are produced. This provided insights into harness manufacturing from a startup-perspective, which proved relevant and helpful when developing a novel manufacturing solution. Around an hour was spent talking with the quality responsible person, which was very helpful.

The aforementioned process diagram was then broken down into even smaller operations, and these were added to a process DSM. The use of the DSM required several iterations, as the definition of a dependency was unclear at first. This produced an illogical order upon triangularisation. Finally, only direct dependencies were mapped, which produced much better results. Although, some operations were still not in a satisfactory order. One example was adding passives, such as corrugated tubes and sleeves, before inserting wires into connector housings. This directly contradicted the guideline from the literature study that control of the wire should not be lost before they are completely terminated. Inserting a branch with several wires through a sleeve would mean exactly that, as wires would have to be identified again. Thus, the substitution to slotted tubes and sleeves was made, which would enable complete wire termination before wrapping. After modularisation of the operations, the DSM, in combination with the interviews, was used to down-select the scope, as including all the operations within a DSM module would make sense from a system perspective.

After the final scope was selected, a function tree was created in a way that was as solution-neutral as possible. The functions were focused around the components of a harness, such as storing, transporting, aligning and mating of these. From this, Braindrawing was used to produce initial ideas of the system-level architecture. Most of these were unfeasible, but this provided a wide lens of all the possible solutions. A modified Pugh matrix was used to down-select the generated system architectures, mainly based on complexity, feasibility and functionality, and one ar-

chitecture showed significantly more promise than the others. The remaining system architecture was then used as a basis for further idea generation within the architecture. Many of these ideas tended to appear in themes and these, in combination with the greater system architecture, led to the creation of nine subsystems. Subsequent idea generation was based on these subsystems. The function tree was also updated to more accurately reflect the functions of the selected architecture, while still being careful not to be solution-specific.

This iterative mindset was also brought to the later part of the product development process. The morphological matrix was updated multiple times, first after the use of elimination matrix, where non-complying solutions were analysed to find the “weak link”, meaning the subsystem idea or ideas that contributed to the elimination, and these ideas were excluded from the future use of the morphological matrix. Later, the morphological matrix was updated again, after the subsystem specific Pugh matrices were completed.

In parallel to these theoretical methods, rapid prototyping was also used as a complement. For example, several subsystem ideas that performed neither good nor bad in the Pugh matrices, were tested in practice to see whether they functioned as imagined or not. Often, the prototype itself performed poorly, mostly due to quick under-refined design or suboptimal tolerances, but the real-life prototype was nonetheless useful for giving a better idea of how a fully designed version would function. In the final round of Pugh matrices of the last set of solutions, two solutions performed similarly well on paper. However, when simulating wire routing of one of these, a fundamental limitation was realised, that was not evident before; the solution could not route wires in some directions. Again, this highlights the benefits and importance of testing early in the development process.

Even if a technologically feasible solution is developed and presented, the solution needs to be viable economically. Thus, an impact assessment was conducted. The assessment starts with the technological side, how the proposed solution would impact manufacturing and product design. This then leads to the economic analysis. Identifying all possible impacts for all these areas is a difficult and time-consuming task. Such work could take up an entire master thesis of itself. Nonetheless, the assessment succeeds in highlighting the consequences for manufacturing, design engineers, product design, and the economics of the company. The NPV formula is especially detailed, even factoring in posts such as operator occupation and machine energy consumption. Of course, the result of this is only as strong as its weakest link. For improving the accuracy of the projection, better estimates of development and machine costs should be used, instead of values generated by AI tools. This would likely reduce costs such as the system unit cost, which is the main factor contributing to the especially long break-even time. A cost estimated based on the costs of a constructed prototype would be a much better way to estimate this investment. Additionally, timings for manufacturing operations could only be obtained for two harnesses. As the result of the NPV calculation varies significantly even for small changes in automation extent, timings for all harnesses should be gathered and weighed to obtain a more realistic projection estimate. Factors like logistics costs, costs for delays in product introduction, costs for deviating batches (both costs for

small fixes, like handling over-lengths but also larger costs, like needing to discard entire harness batches), and knock-on costs would also be relevant to include, but difficult to quantify.

7.4 Reflections on the Proposed Solution

The proposed solution fulfils most of the requirements and the desires. Due to the overall complexity, short time scope and lack of budget, several of the subsystems are still underdeveloped. However, the result provides a platform that could be the basis for future development. Some parts of the system, like the visual terminal aligner system go against our own recommendations from the literature study, that specified to avoid unreliable visual identification systems. The difference here is that identical technology already exists in similar industrial solutions, warranting such a sub-system. Some kind of aligner system is necessary for rotationally asymmetrical terminals, that are widely used in existing harnesses.

This also leads to a broader discussion, as many complexities within the proposed solutions exist due to high component variety. If only round terminals would be used, the aligner system would not need to exist at all and terminating would be simpler. The same conclusion can be drawn for the connector housing storage and holder system. If connectors would share certain dimensions or a reference feature, both systems could be simplified and costs for the entire solution would reduce. Thus, a constant weighing between product variety and manufacturing cost needs to be made. Such compromises are considered even with current manual manufacturing methods, but this would become even more prominent with automation.

In a broader sense, the proposed solution directly addresses all five of the transformation factors within Volvo Group's TTI Strategy. The proposed solution enables faster R&D cycles by facilitating quicker TDB cycles and true Agile methodology as described in Section 6.1.3 reducing cycles from weeks and months to a few days. Implementation of the solution would significantly reduce cost of manufacturing and thus product cost, as described in Section 6.3.2, and likely increase product performance and quality due to the reduction, and ultimately elimination of, human errors in the manufacturing process. Additionally, the strategy states that "Decision-making speed must increase" as one transformation factors. In many cases, decision making will be reduced altogether, as assembly boards are not required any more. Thus, budget negotiations, tooling installation, feasibility studies and other related processes will be significantly reduced or removed altogether. Lastly, the fifth factor involves having "A mindset to challenge everything", which this solution clearly does. Thus, the proposed solution and thesis topic is completely aligned with Volvo TTI's strategic focus.

7.4.1 Integration with Adjacent Manufacturing Systems

The way of integration with the wire preparation machine was not entirely apparent, as several models of wire preparation machines exist with several ways of outputting wires. Thus, some flexibility needed to be built into the solution, to be able to

be integrated with multiple preparation machine variants. The selected way of outputting happened to be along a horizontal rail, but outputting the wires into a bin compartment is not uncommon either. In that case, the bin would have to be placed above the solution, with the wire end sticking out so that the retrieval arm can grasp it. On a broader level, as the wire preparation machine has a higher productivity than a single proposed solution, one preparation machine could be set up to provide wires to several solutions. This distribution system would thus also need to be developed.

The connector storage system would also need to be integrated with central connector housing storage. As information on how these are stored today was unavailable, only the storage system that is directly interacting with the solution was designed. How these connectors are inputted into the system is yet to be defined and developed. One alternative would be manual restocking, but automated stocking would make more sense. In this case, a connector distribution system would also need to be produced. Additionally, unused connector cavities, used in chassis harnesses need to be plugged so that water can not intrude into the connector. Automated plugging solutions exist, but integration with such solution would also need to be made. The plugged connectors would need to be prepared ahead of stocking, and this process would be several harnesses ahead of the routing system at any given time.

Last but not least, integration with the system capable of adding wrappings also needs to be made. While one of the most important considerations was to facilitate for this step, some optimisations could still be made. With the current design, adding slotted corrugated tubes or sleeves would be possible as the flaps of the routing pins can be deformed while wrapping the wires, taping would require more clearance, both horizontally and vertically. To facilitate such operations, optimised and retractable pins could be a solution. Pins could be retracted selectively, increasing clearance locally around the wrapping tool. Although, such a system would undoubtedly come with increased costs and complexity.

7.4.2 System Limitations

Even though most of the requirements and desires are fulfilled, several limitations can be identified in the proposed solution. As it stands, the solution can not produce harnesses with other connectors than the 6 selected within the HDSCS family, due current non-standardised connector designs. Furthermore, the solution is not capable of handling twisted wires. Thus, twisted CAN cables would need to be routed manually, after the automated routing is complete. This is a significant limitation in the system, and would need to be developed for complete automation of the routing process. Several potential solutions have been ideated, but the time scope did not allow for more detailed development of these.

Furthermore, the system is not capable of handling thicker power cables at all. Due to the design of the routing system, that takes a vertically fed wire which later curves down to be horizontal at the routing tool, the system has an inherent limitation in the bend radius of the wire, and thus the gauge of the wire.

The incompatibility with splices was almost inevitable, as such features would increase machine complexity to an unsustainable level. Handling DLOs was considered to be challenging enough, but handling non-linear deformable objects would require several more grippers and special tools. The use of splices is a topic that is more widely discussed, with some companies using them, and others not. Automation may finally provide a strong enough incentive to transfer the functionality of splices to internal connections, where signals are distributed to the terminals of several wires.

7.5 Reflections on the Thesis Subject

Starting the thesis and learning more about the subject has been both educational and challenging. Initially, the task seemed intimidating as we ventured into an area with a clear gap in the literature. We were humble about the fact that we set out to automate a process that experts from multiple fields had struggled with for many years. Rather than following the same approaches that had been attempted before, we wanted to look at the problem through a new lens and explore whether this task could be solved in a way that had not been tried before. Given the size and complexity of the topic, we approached the task with an open mind, keeping our options broad at the outset to identify where a solution was most needed from both theoretical and practical perspectives. This approach allowed us to decompose the complex task into smaller, more manageable steps; a way of working that became a recurring theme throughout the thesis.

Working with such a complex and genuinely innovative topic and developing a new product from the ground up is an opportunity that rarely presents itself. This has been highly insightful and has taught us how to tackle large, ill-defined tasks in a systematic way. Although we gradually decomposed the project scope to deliver a solution that provides value to both Volvo and academia, the task remained substantial and priorities had to be made. Many comparative methods such as benchmarking have not been able to be used, as comparative products do not yet exist. While we sometimes wanted to continue iterating and improving certain solutions, time did not allow it, and we therefore needed to move on. As an example, only two to three days could be spent to ideate, develop, design, test and iterate for each sub-system before we needed to move on to the next sub-system. It would have been interesting to continue working on the proposed solution, improving its sub-systems and attempting to integrate *Adding Wrappings* as well, as this would have significantly increased its potential. Nevertheless, we are happy to have contributed a foundation that can support future development in this area.

8

Conclusion

In conclusion, the thesis set out to reduce wiring harness manufacturing cost by 15 %, by automating select parts of the process and proposing a manufacturing solution for the same. The aim was to develop a high-level geometric concept of such a solution with focus on the layout and integration with the wider manufacturing process. Additionally, the aim was to evaluate the impact of implementation of the solution on the manufacturing process, harness design engineering, harness components and the economics of the solution implementation. The purpose was to address the challenge of automating this predominantly manual and costly process, and to provide the industry with a foundation for future development.

While the cost reduction of 15 % could not be achieved with the proposed solution alone, the economic impact assessment showed that wider automation of the process can result in much larger savings long-term. A geometrical concept in the form of a CAD model of a system capable of routing and terminating signal wires was produced, which opens the doors to automating further operations such as adding sleeves, tubes and tape. The impact of the proposed solution was investigated, achieving automation of around 20 % of the current process duration, on average. The impact of a future scenario with a further developed version of the solution was also evaluated, automating approximately 95 % of the current process duration. While the impact of the proposed solution would eliminate the need for assembly tables and thus reduce lead times for product changes, such a scenario would likely not lead to large changes in the workforce, with many assembly workers remaining and being split between operating the system and filling the need for increased productivity for adding harness protection. However, for the further developed scenario, workforces are expected to be replaced to a large extent, which also pose ethical questions. In such a scenario, manufacturing could be moved to be in connection to the final truck assembly site, reducing transport times, carbon emissions and enabling lean and just-in-time production of harnesses, further improving sustainability.

The research questions that guided this thesis have all been answered. The major challenges with automating wiring harness manufacturing have been addressed, and the strategies for overcoming these challenges guided the development of the proposed solution. This resulted in a system architecture consisting of a universal assembly board with pins capable of handling the desired variants. Importantly, the architecture is designed to support future integration of adjacent and subsequent machines, as well as the implementation of control logic for translating X2ML files into machine instructions, without imposing limitations on these extensions. It is concluded that the overall impact of this solution can be considered promising from an economic perspective. From a design and manufacturing perspective, the extent

of automation would need to be expanded and require changes in both processes and component design.

During this thesis, a solution has been developed that solves the defined problem and fulfils the needs. Although steps have been taken in the right direction in this thesis, the task is not small. Automating to the extent of the scope of this thesis makes little sense economically or process-wise, but near-full automation could provide a significant competitive advantage for the company where it is implemented, though requiring significant investments. While the technology necessary for near-full automation is deemed to exist, current harnesses include too many variables and non-standardised parts. Thus, all stakeholders and suppliers need to adapt, standardise interfaces and design for automation. If the industry is willing to adapt, significant savings in both costs, lead times and development time could be realised.

Finally, recommendations to the various stakeholders will be presented in the next section.

8.1 Recommendations and Further Development

Despite the proposed solution fulfilling most of the requirements and desires, the authors do not recommend developing the solution as-is. The solution needs to be developed further, adding missing functionality like handling of twisted wires and refining integration with wire preparation machines and connector storage systems. The system also needs to be refined to facilitate for the next step in the process, either adding wrappings, adapters and tape directly on a board, but improving the routing pin design to facilitate for this, or by being able to move the assembly board with the routed harness - possibly by rails - and replacing it with an empty board. Apart from machine hardware, its firmware and the software capable of converting design files into firmware instructions also needs to be developed. Connectors need to be redesigned to suit automation. After these changes, a full-scale prototype needs to be constructed to further evaluate function and achievable performance.

After this, a new impact assessment should be conducted to evaluate viability with these improved performance metrics. The relevant partners and stakeholders need to be gathered and partnerships need to be established before a development plan is set up. Wide-ranging partnerships ranging both suppliers, OEMs and component manufacturers would ensure industry-wide alignment on automation.

A further developed and refined version of the solution would be more realistic to implement for cab harnesses, as these do not have as much wrappings as chassis harnesses, thus resulting in a higher level of automation. Finally, functionality that is capable of adding wrappings, like slotted corrugated tube, slotted DLPS sleeves and tape, marking tape, cable ties as well as adding manifolds and backshells. Only then could full implementation commence.

As the implementation costs are substantial as shown in the impact assessment, especially for the 95 % automation scenario, development and patenting of the technology are recommended instead of implementation by Volvo Group themselves.

This way, Volvo could license the technology within the patent, earn royalty fees for each implementation and use, and tap in to the entire automotive market instead of only their own market share. The NPV curve presented in Section 6.3.2 would not have the significant negative curve after development, as implementation costs would not be handled by Volvo. Thus, both investment costs and payback time would be reduced. This would also lower risks for Volvo.

The overwhelming question for stakeholders is not whether harness manufacturing will be automated or not, but rather when it will be automated. To prepare for this industry-wide change, recommendations to the different stakeholders follow below.

Management at Volvo TTI and Volvo Group are recommended to drive the change towards automation, either exploring options in-house or collaborating with companies in the wiring harness industry. Leading the development of automated harness manufacturing would provide a competitive advantage for the involved actors. This advantage of zero-cost for product change would be especially significant for a company like Volvo Group, that provide many products with extensive ranges of variants.

For product owners and wiring engineers, designing harnesses for automation today would reduce the workload of tomorrow. If harnesses are already today designed with fewer connector families, no splices, less complex wrappings, and slotted or two-part wrappings, harnesses would be automated easier and reducing the need of redesigning once automated manufacturing is introduced.

Finally, standardisation engineers and industry representatives need to drive progress towards reduced amount of terminal and connector families and changing the design of these to improve automated processing. For example, changing to rotationally symmetric terminals, and changing connector design to introduce common dimensions and a common grip- and reference feature across families would greatly facilitate automated manufacturing.

Lastly, to quote one of the interviewed workshop technicians, automation of wiring harness manufacturing is “difficult... but not impossible”, but requires full alignment and stakeholder collaboration across the industry.

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A

Process Dependency Structure Matrix

	Twist wires (if req.)	Measure wire	Cut wire	Strip wire end 1	Install grommet on wire end 1 (if req.)	Crimp terminal to wire end 1	Strip wire end 2	Install grommet on wire end 2 (if req.)	Crimp terminal to wire end 2	Create splice (if req.)	Place connector housing	Route wires on assembly board	Insert terminals into connector housings	Bundle wires using tape and/or cable ties	Measure DLPS sleeve (if req.)	Cut DLPS sleeve (if req.)	Install DLPS sleeve (if req.)	Measure corrugated tube (if req.)	Cut corrugated tube (if req.)	Install corrugated tube (if req.)	Install manifolds (if req.)	Install back shells and its cable ties (if req.)	Wrap DLPS tape over branchings and transitions	Add mark tape and cable ties and clips	Electrical and continuity testing	Add harness-level markings and labels	Kitting	Final inspection	Packing
Twist wires (if req.)	#																												
Measure wire		#																											
Cut wire		X	#																										
Strip wire end 1				#																									
Install grommet on wire end 1 (if req.)					#																								
Crimp terminal to wire end 1				X	X	#																							
Strip wire end 2			X				#																						
Install grommet on wire end 2 (if req.)								#																					
Crimp terminal to wire end 2						X	X		#																				
Create splice (if req.)				X						#																			
Place connector housing											#																		
Route wires on assembly board	X		X							X		#																	
Insert terminals into connector housings					X			X		X		#			X		X												
Bundle wires using tape and/or cable ties									X				#																
Measure DLPS sleeve (if req.)														#															
Cut DLPS sleeve (if req.)													X		#														
Install DLPS sleeve (if req.)												X		X		#													
Measure corrugated tube (if req.)																	#												
Cut corrugated tube (if req.)																X		#											
Install corrugated tube (if req.)												X					X		#										
Install manifolds (if req.)												X		X			X		#										
Install back Shells and its cable ties (if req.)									X	X			X		X		X			#									
Wrap DLPS tape over branchings and transitions													X		X		X		X										
Add mark tape and cable ties and clips														X		X	X		X										
Electrical and continuity testing																				X									
Add harness-level markings and labels															X		X	X		X									
Kitting																						X	X		#				
Final inspection	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	#	
Packing																											X	#	

Figure A.1: Initial process DSM

A. Process Dependency Structure Matrix

	Strip wire end 1	Twist wires (if req.)	Measure wire	Cut wire	Install grommet on wire end 1 (if req.)	Install grommet on wire end 2 (if req.)	Place connector housing	Measure DLPS sleeve (if req.)	Cut DLPS sleeve (if req.)	Measure corrugated tube (if req.)	Cut corrugated tube (if req.)	Strip wire end 2	Create splice (if req.)	Crimp terminal to wire end 1	Crimp terminal to wire end 2	Route wires on assembly board	Bundle wires using tape and/or cable ties	Install DLPS sleeve (if req.)	Install corrugated tube (if req.)	Install manifolds (if req.)	Insert terminals into connector housings	Install back shells and its cable ties (if req.)	Wrap DLPS tape over branchings and transitions	Add mark tape and cable ties and clips	Electrical and continuity testing	Add harness-level markings and labels	Kitting	Final inspection	Packing
Strip wire end 1	#																												
Twist wires (if req.)		#																											
Measure wire			#																										
Cut wire			X	#																									
Install grommet on wire end 1 (if req.)					#																								
Install grommet on wire end 2 (if req.)						#																							
Place connector housing							#																						
Measure DLPS sleeve (if req.)								#																					
Cut DLPS sleeve (if req.)								X	#																				
Measure corrugated tube (if req.)										#																			
Cut corrugated tube (if req.)									X	#																			
Strip wire end 2				X							#																		
Create splice (if req.)	X											#																	
Crimp terminal to wire end 1	X				X								#																
Crimp terminal to wire end 2						X					X			#															
Route wires on assembly board		X		X								X			#														
Bundle wires using tape and/or cable ties													X		#														
Install DLPS sleeve (if req.)								X						X		#													
Install corrugated tube (if req.)									X					X			#												
Install manifolds (if req.)														X	X	X		#											
Insert terminals into connector housings						X							X	X	X				#										
Install back shells and its cable ties (if req.)														X	X	X			X	#									
Wrap DLPS tape over branchings and transitions															X	X				X	#								
Add mark tape and cable ties and clips																X	X	X			X	#							
Electrical and continuity testing																				X		#							
Add harness-level markings and labels																	X	X	X				#						
Kitting																					X	X		#					
Final inspection	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	#	
Packing																											X	#	

Figure A.2: Solved process DSM

A. Process Dependency Structure Matrix

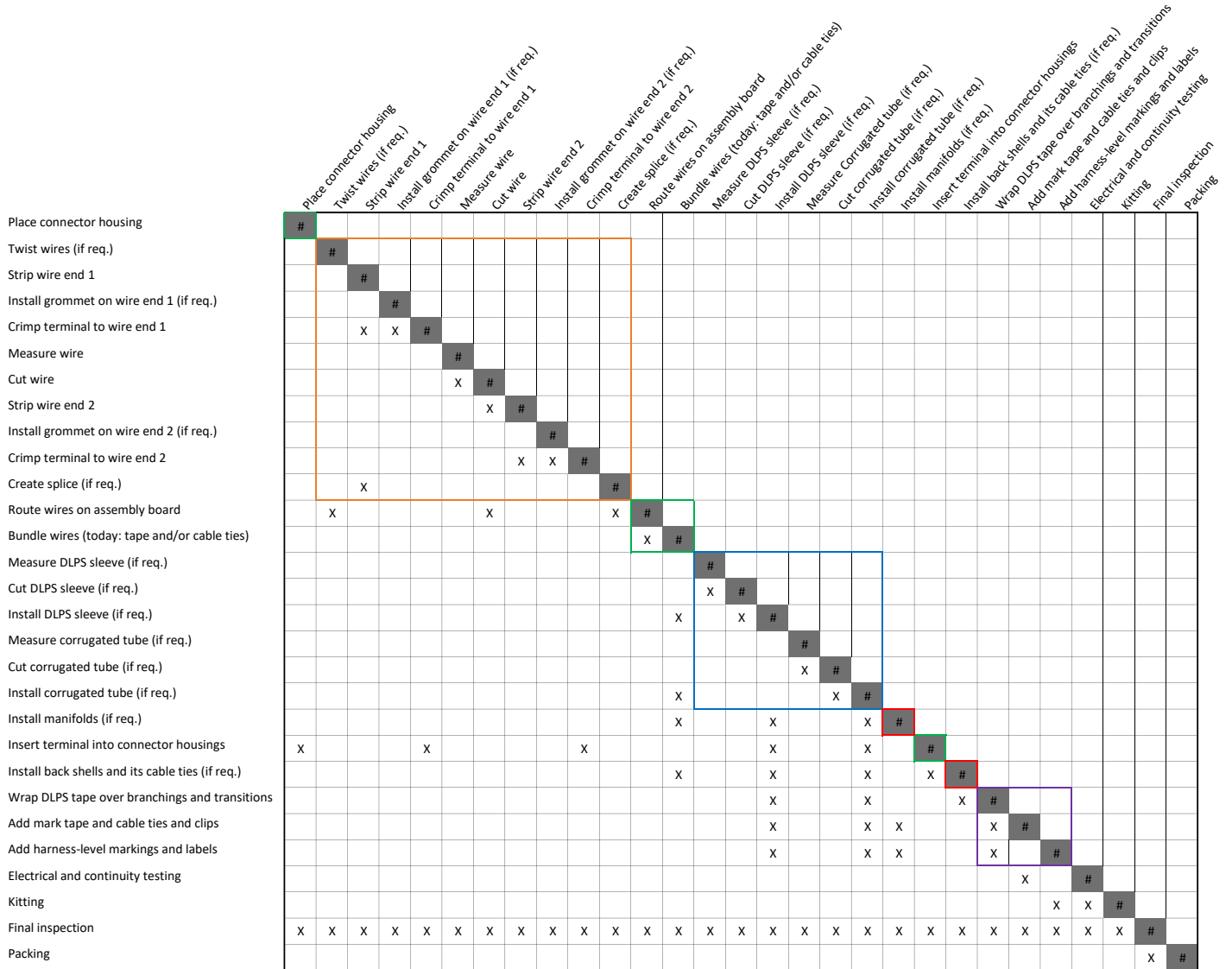


Figure A.3: Solved process DSM (first refinement)

Note. Phases of the wiring harness manufacturing process.

1. **Green:** Wiring operations
2. **Orange:** Wire preparation
3. **Blue:** Adding wrappings
4. **Red:** Adding adapters
5. **Purple:** Taping, marking

A. Process Dependency Structure Matrix

	Twist wires (if req.)	Strip wire end 1	Install Grommet wire end 1 (if req.)	Crimp terminal to wire end 1	Measure wire	Cut wire	Strip wire end 2	Install grommet on wire end 2 (if req.)	Crimp terminal to wire end 2	Create splice (if req.)	Place connector housing	Route wires on assembly board	Insert terminal into connector housings	Bundle wires (today: tape and/or cable ties)	Measure slotted DLPS sleeve (if req.)	Cut slotted DLPS sleeve (if req.)	Install slotted DLPS sleeve (if req.)	Measure slotted corrugated tube (if req.)	Cut slotted corrugated tube (if req.)	Install slotted corrugated tube (if req.)	Install manifolds (if req.)	Install back shells and its cable ties (if req.)	Wrap DLPS tape over branchings and transitions	Add mark tape and cable ties and clips	Add harness-level markings and labels	Electrical and continuity testing	Kitting	Final inspection	Packing
Twist wires (if req.)	#																												
Strip wire end 1		#																											
Install Grommet wire end 1 (if req.)			#																										
Crimp terminal to wire end 1		X	X	#																									
Measure wire					#																								
Cut wire				X	X	#																							
Strip wire end 2						X	#																						
Install grommet on wire end 2 (if req.)								#																					
Crimp terminal to wire end 2						X	X	#																					
Create splice (if req.)		X							#																				
Place connector housing										#																			
Route wires on assembly board	X								X																				
Insert terminal into connector housings				X					X							X		X											
Bundle wires (today: tape and/or cable ties)										X																			
Measure slotted DLPS sleeve (if req.)															#														
Cut slotted DLPS sleeve (if req.)															X	#													
Install slotted DLPS sleeve (if req.)															X		X	#											
Measure slotted corrugated tube (if req.)																		#											
Cut slotted corrugated tube (if req.)																	X	#											
Install slotted corrugated tube (if req.)															X			X	#										
Install manifolds (if req.)													X				X		X	#									
Install back shells and its cable ties (if req.)												X	X				X		X	#									
Wrap DLPS tape over branchings and transitions																	X		X		X	#							
Add mark tape and cable ties and clips																	X		X	X		X	#						
Add harness-level markings and labels																	X		X	X		X		#					
Electrical and continuity testing																					X			#					
Kitting																						X	X		#				
Final inspection	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	
Packing																											X	#	

Figure A.4: Solved process DSM (final refinement)

Note. Phases of the wiring harness manufacturing process.

1. **Orange:** Wire preparation
2. **Green:** Wiring operations
3. **Blue:** Adding wrappings
4. **Red:** Adding adapters
5. **Purple:** Taping, marking

B

Requirement Specification

Requirement Specification - Wiring Harness Manufacturing Solution

Req Num.	Objective/Goal	Justification	Requirement	Value Functional Requirements	R/D/O	Evaluation Method	Reference	Comment
1.1	Functionality	Specifying solution function	The solution shall manufacture a bundled harness for signal wires with branches and mounted connector housings from fully prepared wire lengths	Y	R	Evaluate* functionality through various means such as CAD	Volvo TTI/Authors	*Evaluation can be done after a preliminary design, either through geometric evaluation, comparison against existing machines and evaluation with the help of CAD or simple 3D prints
1.2	Manufacture wiring harness	Accomodate to the specified design	The solution shall manufacture harnesses according to a compatible harness design defined in the X2ML file	Y	R	Compare the manufactured wiring harness against schematics, verify	Volvo TTI	
1.3	Automation	Reduce labor cost, manufacturing time and improve safety	The solution should not require any human intervention or collaboration during manufacturing	Y	D5	Can not be evaluated for prototype; final solution needs to be implemented before evaluation can occur	Authors	Even if total automation for steps in 1.1 can be thought to be implemented, the need for minor adjustments/interventions during the process can only be evaluated once the final full scale solution is implemented
1.4	Reconfigurability	Reduce setup time ideally to 0, reduce need for human intervention	Solution needs to be able to be reconfigured to manufacture a different harness with no manual effort	Y	D3	Evaluate whether harness specific tooling is added manually or not within solution	Volvo TTI/Authors	
1.5	Reconfigurability	Reduce manufacturing time, reduce need for human intervention	Make possible to add passives such as slotted corrugated tube and slotted DLS sleeves without manually moving the wiring harness	Y	D4	Evaluate* functionality through various means such as CAD and see if sufficient spacing exists for necessary operations	Authors	
Performance Requirements								
2.1	Speed	Solution should be more productive than the current manual way of working	Harness manufacturing time of current manufacturing	≤ 85% of current	D5	Theoretical evaluation as prototype construction is not feasible. Compare functions and process steps with existing products and add the time of the different operations	Authors	
2.2	Cost	Solution should be cheaper to operate than the current manual way of working	10-year manufacturing cost of current manufacturing	≤ 85% of current	D5	Financial analysis / NPV calculation	Authors, Volvo TTI	Due to confidentiality restrictions, figures relevant to setting a target cost are not expected to be acquired
2.3	Tolerance	Carry out precise operation to reduce failure rate	The solution should provide a precision with respect to the tolerances needed for various operations resulting in a failure rate below the limit in 2.4	Y	R	Can not be evaluated for prototype; final solution needs to be implemented before evaluation can occur	Authors; consulted ISO 22514-2:2026 chapter 5 specifically, ISO 22514-1:2014	Used primarily for technology selection in concept phase. Difference between diameter of terminal and housing cavity is 0.8 mm
2.4	Reduce failure rate	Minimise downtime and manufacture of faulty harnesses	The fraction of non-conforming harnesses should be below specified limit	RPN < 265	R	Compare PRMEA of current way of working with the solution	Authors; IEC 61709	
Harness Characteristics								
3.1	Wire gauge sizes	Accommodate different wire sizes	The solution shall handle wires with certain cross-sectional areas	0.75 mm² to 2.5 mm²	R	Evaluate* with wires at both extremes, verify reliable handling	Volvo TTI	*Evaluation can be done after a preliminary design, either through geometric evaluation, comparison against existing machines and evaluation with the help of CAD or simple 3D prints
3.2	Possible produced harnesses	Needed for dimensioning wire throughputs and transport conduits	Maximum possible diameter of prepared wire	5.9 mm	R	Evaluate* function with maximum diameter of prepared wire; check entire route from start to finish to see if the thickness is interfering with anything	Volvo TTI/Authors	MCP 1.5 & 2.8 as example housings. Max diameter of prepared wire is SWS, largest is part number 970773 with diameter 5.6±0.3 mm
3.3	Possible produced harnesses	Needed for dimensioning wire throughputs and transport conduits	Minimum possible diameter of prepared wire	0.6 mm	R	Evaluate* function with minimum diameter of prepared wire; check entire route from start to finish to see if the thickness can be handled	Volvo TTI/Authors	Smallest wire diameter for MCP 1.5 is 1.2 mm. However, the tab of 60113652 is even smaller, 0.6 mm in size. Grommet 60113654 is 3.9 mm in diameter
3.4	Possible produced harnesses	Needed for dimensioning wire throughputs and transport conduits	Maximum possible length of stiff end of prepared wire (terminal + grommet)	32.8 mm	R	Evaluate* for the longest stiff end; check entire route from start to finish to see if the thickness can be handled	Volvo TTI/Authors	MCP 1.5 & 2.8 as example housings. Max grommet seal length (outside terminal) is 4.3mm for 970773, terminal is (15.5±0.4) + (15.6±1.3) mm = 31.1±1.7 mm. Receptacle is only max 27.1±1.3 mm
3.5	Possible produced harnesses	Needed for dimensioning wire throughputs and transport conduits	Number of wire colors	11	D4	Evaluate* if machine can handle colors (if applicable)	Volvo TTI	As defined in internal standard S15-0002, chapter 2.2.1.2.5
3.6	Possible produced harnesses	Needed for dimensioning wire throughputs and transport conduits	The solution should be able to route and handle long wires	up to 7000 mm	D2	Evaluate* function with maximum length of the wiring harness	Volvo TTI/Authors	Approximate value for longest configurable length, connector-to-connector. An indication, not an exact value. Desire, as shorter modular lengths can be an alternative
3.7	Possible produced harnesses	Needed for dimensioning wire throughputs and transport conduits	The solution should be able to handle the harness with the maximum number of connector housings	122 housings at once	D2	Evaluate* function with maximum number of housings	Volvo TTI/Authors	Maximum connectors on Mainfront drawing. Not all connectors on drawing are used for a given harness. Though number may increase if connectors need to be broken up to not have connectors with mixed terminal sizes
3.8	Possible produced harnesses	Needed for dimensioning wire throughputs and transport conduits	The solution should be able to route harnesses with the specified diameter	3 mm < X < 50 mm	R	Evaluate* minimum and maximum thicknesses	Volvo TTI/Authors	Max harness diameter was specified as 40 mm, Authors added 10 mm more for future-proofing reasons. Smallest "harness" is a single 0.75 mm² wire, around 3 mm in diameter
3.9	Possible produced harnesses	Needed for dimensioning wire throughputs and transport conduits	Terminal types	MCP 1.5 & 2.8	R	Evaluate* function with the specified terminal types	Volvo TTI/Authors	Sizes set to fulfill requirement 3.1, thus MCP 6.3 and up are excluded. Authors selected MCP family for its extensive usage for chassis wiring. Refer to drawings for terminal dimensions
3.10	Possible produced harnesses	Needed for dimensioning wire throughputs and transport conduits	The solution should be able to handle the harness with the maximum number of connector housings	6 referenced housings	R	Evaluate* function with maximum number of housings	Volvo TTI/Authors	Selected housings for design of a prototype system: HDSCS 1.5; Tab and rec. for 3 and 18 pos., HDSCS Mixed (1.5 & 2.8); Tab and receptacle, 10 positions (6+4)

Requirement Specification - Wiring Harness Manufacturing Solution

Req Num.	Objective/Goal	Justification	Requirement	Value	R/D/O	Evaluation Method	Reference	Comment
Safety Requirements								
4.1	Safety	Reduce risks and injuries	Safety perimeter should be established, marked and if needed the solution should be enclosed	Y	R	Evaluate safety risks of design; take necessary design action	Authors; ISO 12100:2010, chapter 6.3 and 6.4, SS-EN ISO 13854:2019 chapter 4.2	
4.2	Safety	Prevent unexpected start-up during human interaction	Solution should electrically disconnect moving systems at the end of cycle; should require manual action for reconnection of electrical supply	Y	R	Evaluate safety risks of design; take necessary design action	Authors; Internal Standards 8010.3, specifically chapters 5 and 6	
4.3	Safety	Reduce risks and injuries	Solution should provide sufficient safety precautions such as markings, sensors, lights and guardrails showing reach in compliance with internal standards	Y	R	Evaluate safety risks of design; take necessary design action, FMEA of As-is	Authors; Internal Standards 8010.3, specifically chapters 5 and 6	
4.4	Safety	Enable operator to maintain control during automated operation	Solution shall provide operators with the ability to safely pause or stop operation at any time during the cycle	Y	R	Test stop function during operation; verify that the solution halts safely and indicates stopped state (if applicable)	Authors; ISO 12100:2010, chapter 6.2.11	
Quality Requirements								
5.1	Compliance with quality standards	To follow wiring harness manufacturing standards	Compliance with the internal standard 515-0002	Y	D3	Evaluate if there is any part of the solution that would inherently contradict following the standard	Volvo TTI	
5.2	Compliance with quality standards	To follow wiring harness manufacturing standards	Compliance with the trade standard IPC/WHMA-A-620	Y	R	Evaluate if there is any part of the solution that would inherently contradict following the standard	Volvo TTI/Supplier	
5.3	Maintain high product quality	The wiring harness quality shall not be compromised	Product quality should be at a minimum at the level of the current production methods	Y	R	Evaluate* if the wiring harness manufactured by the solution is of the same quality (or better) as a manually manufactured wiring harness	Authors/Volvo TTI	
5.4	Maintain high production quality	The production process quality shall at least be maintained for a new production process	Productivity and uptime should be at a minimum at the level of the current production methods	Y	R	Evaluate* whether the solution's productivity and uptime over time meet or exceed current production levels, and whether this justifies automating the wiring operation	Authors	
Integration Requirements								
6.1	Design for system integration	Enable integration of solution into larger production line	The solution geometry shall be designed for easy integration with prior and subsequent production systems	Y	D5	Design review / CAD integration analysis	Authors	
Sustainability and Repairability Requirements								
7.1	Material efficiency	Minimise manufacturing waste and reduce material costs	The solution shall achieve wire utilisation equal to or better than the current manual manufacturing process	Y	D2	Measure material input vs. finished harness weight for both manual and automated manufacturing	Authors	
7.2	Repairability	Enable maintenance and extend life of solution	The solution shall be designed for repairability, with modular components	Y	D3	Visual inspection; operator feedback	Authors	
7.3	Use of non-standard parts	Reduce manufacturing, service and repair costs	Do not use custom-manufactured parts; only use off-the-shelf components	Y	D1	Parts list review	Authors	
Environmental Requirements								
8.1	Operating temperature	The solution should be able to operate within existing factory conditions	Ability to operate within nominal working temperature for human workers	20°C to 26°C	R	Consider during engineering. Verify by testing solution within set operating conditions	Authors; SS-EN 7730:2006	
8.2	Operating humidity	The solution should be able to operate within existing factory conditions	Ability to operate within nominal working humidity for human workers	30% to 70%	R	Consider during engineering. Verify by testing solution within set operating conditions	Authors; Generalised humidity range for work environments	
8.3	Limit environmental effects	The solution needs to prevent a deterioration of working conditions for human workers	Limit generated temperature	Depends on surface material and exposure time	D1	Consider during engineering. Verify by testing solution, follow steps in ISO 13732-1:2008 §7.2b	Authors; ISO 13732-1	
8.4	Limit environmental effects	The solution needs to prevent a deterioration of working conditions for human workers	Limit generated sound to acceptable levels for prolonged human exposure	< 85 dB, including other sources in the facility	R	Consider during engineering. Verify by testing solution	Authors; AFS 2005:16	

C

Process Failure Mode and Effects Analysis

Table C.1: Process Failure Mode and Effects Analysis (PFMEA) of manual solution

Process Failure Mode	S	O	D	RPN	Current Measures
Incorrect routing of a wire	4	2	3	24	Wrongly routed wire will be relatively easy to notice, as it would be outside forks and rest of the branch
Terminal in wrong connector cavity	10	3	1	30	Will be detected during electrical testing
Terminal in right cavity but wrongly inserted	8	4	1	32	Small deviations likely detected shortly after by worker, otherwise during testing
Branch not routed/bundled correctly (too short/long)	5	2	5	50	Routing forks will be empty, however may be difficult to notice if parallel forks exist
Wrong connector used	6	2	1	12	Connector holder is shaped so only the right connector can be inserted
Connector placed wrongly	6	2	1	12	Connector holder is shaped so only the right connector can be inserted
Wrong wire used	5	3	7	105	Small deviations likely not detected until final assembly
Total RPN	265				

Table C.2: Process Failure Mode and Effects Analysis (PFMEA) of proposed solution

Process Failure Mode	S	O	D	RPN	Proposed Measures
Incorrect routing of a wire	4	1	2	8	Log actual movements and compare with “instructions”; Notify human upon deviation
Terminal in wrong connector cavity	10	1	2	10	Log actual movements and compare with “instructions”; Notify human upon deviation
Terminal in right cavity but wrongly inserted	8	2	1	16	Measure inserting distance and resistance
Branch not routed/bundled correctly (too short/long)	5	1	2	10	Log actual movements and compare with “instructions”; Notify human upon deviation
Wrong connector used	6	1	2	12	Measure inserting distance and gripping resistance; Log actual movements and compare with “instructions”; Notify human upon deviation
Connector placed wrongly	6	1	2	12	Log actual movements and compare with “instructions”; Notify human upon deviation
Wrong wire used	5	1	2	10	Will be detected while routing (feeding distance will not match file). Colour detection may need additional sensor
Total RPN				78	

D

List of Generated Subsystem Ideas

Table D.1: Subsystem ideas for subsystems A-E with corresponding descriptions

ID	Subsystem idea	Description
A1	Static robot arm (one end)	Independent robot arm that grips one wire end
A2	Static robot arm (two ends)	Independent robot arm that grips two wire ends
A3	Integrated arm (one end)	Integrated on subsystem D tooling head
A4	Integrated arm (two ends)	Integrated on subsystem D tooling head
B1	Belt feeder	Adaptable width twin belts feeding downward
B2	Offset roller feeder	Adaptable width rollers feeding downward
B3	Flexible organic feeder	Multi-directional flexible feeder feeding downward
B4	Flexible bristle feeder	Self-adjusting bristle wheels downward feed
B5	No feeder	For solutions not utilising a feeder
C1	Twist aligners	Wire fed through passive aligner to orient terminal
C2	Roller aligners	Wire fed through roller aligners to orient terminal
C3	Visual rotating aligner	Rotary alignment with vision feedback
C4	Pressure-sensing rotating aligner	Rotary alignment with force sensing
C5	Dip aligner	Dip-and-raise alignment for terminal orientation
C6	No aligner	If alignment is handled in another subsystem
D1	Cartesian CNC system	3-axis Cartesian gantry system with CNC
D2	Robot arm	6-axis robot arm
D3	Polar robotic system	Centrally positioned with radial, angular, and vertical axes
D4	CoreXY gantry	Belt-driven XY gantry
D5	Cable-Driven Parallel Robot	Cable-driven system with suspended moving platform
D6	Delta parallel robot	High-speed with triangular arm kinematics for pick-and-place
E1	Regular pins	Perpendicular pins on assembly board
E2	Puzzle pins	Puzzle-pattern pins allowing connector housings to be inserted
E3	Pins with rubber flaps	Pins with rubber flaps that are vertically adjustable
E4	Hybrid pins	Connector placed on holder, then holder placed on straight pins
E5	Pins with sponge tops	Pins with sponge tops that are horizontally adjustable
E6	Curved flexible pins	Curved pins that are horizontally adjustable
E7	Straight 45° angled flexible pins	Angled pins that are vertically adjustable

D. List of Generated Subsystem Ideas

Table D.2: Subsystem ideas for subsystems F-I with corresponding descriptions

ID	Subsystem Idea	Description
F1	Direct feed	Wire ends are directly fed into connector housing
F2	Traditional gripper	Wire ends are inserted with a gripper
F3	Integrated router and gripper	Insert wire end 1, route backward, then insert wire end 2
F4	Pneumatic insertion	Pneumatic cylinder drives insertion of terminal
G1	Hanging back shell lip storage	Connectors hang with cavities facing upward for easy pick-up
G2	Stacked top-down storage	Connectors are stacked vertically and picked up at bottom
G3	Linear feeder storage	Feeder transporting connector into available slot
G4	Mixed feeder storage	Feeder transporting different connectors into available slot
G5	Bin storage	Different types of Connectors scattered in a storage box
H1	Three-point gripper	Grippers with reference points connected to subsystem D
H2	Spring gripper with 1D gantry	1-axis gripper using a spring to distribute
H3	Retractable grasp	Adjusts to connector holder, connected to subsystem D
H4	Manual distribution	A human retrieves and distributes connector housing
H5	Robotic gripper with 1D gantry	3-axis robotic gripper with connector reference point
H6	Platforms with planar motors	Connector holder that is movable and can retrieve
H7	Sliding puzzle system	Board-mounted connector holder on tracks that can move
I1	Pin-connector table (Vertical)	Relates to E4, connector cavities are vertical
I2	Fixation via H6/H7	Sub-solution I2 is integrated in H6/H7
I3	Table edge system (Horizontal)	Connectors are fixed on the edges, connector cavities are horizontal
I4	Pin-connector table (Horizontal)	Relates to E2, connector cavities are Horizontal
I5	Traditional connector holders	Same tooling that is used currently

E

Relationship Between Screening Criteria and Requirements

Table E.1: Criteria mapping to requirements for system architecture

Criteria	Requirement/Desire
System Architecture	
Feasibility	1.1, 1.2
Low complexity	2.2, 2.4, 6.1, 7.2, 7.3
Expandability	1.2, 1.4, 3.5-3.7, 6.1
Compatibility	6.1, 7.3
Reconfigurability	1.4, 3.1-3.4, 3.9
Accuracy	2.3, 5.1, 5.2, 5.3, 5.4

Table E.2: Criteria mapping to requirements for subsystems A-F

Criteria	Requirement/Desire
Subsystem A	
Low complexity	2.2, 2.4, 6.1, 7.2, 7.3
Performance	1.4, 2.1, 5.4
Accuracy	2.3, 5.1, 5.2, 5.3
Compactness	1.1, 1.2
Subsystem B	
Low complexity	2.2, 2.4, 6.1, 7.2, 7.3
Performance (feeding speed)	1.4, 2.1, 5.4
Accuracy (precision of feeding)	2.3, 5.1, 5.2, 5.3
Compactness (physical size)	1.1, 1.2
Adaptability (handling different wire sizes and irregularities)	1.2, 3.1-3.10
Subsystem C	
Low complexity (both of aligner and of other added systems)	2.2, 2.4, 6.1, 7.2, 7.3
Performance (speed)	1.4, 2.1, 5.4
Reconfigurability	1.4, 3.1-3.4, 3.9
Compactness	1.1, 1.2
Reliability (of correct orientation achieved)	1.2, 1.3, 2.3, 2.4
Subsystem D	
Low complexity	2.2, 2.4, 6.1, 7.2, 7.3
Performance (speed)	1.4, 2.1, 5.4
Accuracy	2.3, 5.1, 5.2, 5.3
Reliability (of main positioning system)	1.1-1.3, 2.4, 5.4
Expandability	1.2, 1.4, 3.5-3.7, 6.1
Load capacity	2.1, 2.3, 2.4
Subsystem E	
Low complexity	2.2, 2.4, 6.1, 7.2, 7.3
Wire retaining	1.1, 1.3, 1.4, 6.1
Ease of routing	2.1, 2.4, 3.1, 3.8
Ease of harness removal	1.5, 5.4, 6.1
Ease of bundling	1.5, 5.4, 6.1
Harness routing flexibility	1.2, 3.1-3.10
Subsystem F	
Low complexity	2.2, 2.4, 6.1, 7.2, 7.3
Performance	1.4, 2.1, 5.4
Accuracy	2.3, 5.1, 5.2, 5.3
Compactness	1.1, 1.2

Table E.3: Criteria mapping to requirements for subsystems G-I

Criteria	Requirement/Desire
Subsystem G	
Low complexity	2.2, 2.4, 6.1, 7.2, 7.3
Reliability	1.3, 1.4, 2.4, 5.4
Precision	2.3, 5.1, 5.2, 5.3
Compactness	1.1, 1.2
Reconfigurability	1.4, 3.7, 3.9, 3.10
Expandability	1.2, 1.4, 3.7, 6.1
Ease of stocking (inserting connectors)	2.1, 5.4
Subsystem H	
Low complexity	2.2, 2.4, 6.1, 7.2, 7.3
Performance (speed)	1.4, 2.1, 5.4
Precision	2.3, 5.1, 5.2, 5.3
Compactness	1.1, 1.2
Reconfigurability	1.4, 3.7, 3.9, 3.10
Expandability	1.2, 1.4, 3.7, 6.1
Subsystem I	
Low complexity	2.2, 2.4, 6.1, 7.2, 7.3
Ease of fixation	1.4, 2.3, 2.4
Connector flexibility (large/small limitations)	1.2, 3.7
Ease of termination (routing tool repositioning)	1.1, 1.2, 2.3, 2.4
Robustness	2.3, 2.4, 5.4

F

Pugh Matrices for Subsystem Concept Screening

Subsystem A: Retrieve Wire from Wire Preparation Machine

Criterion	Weight	Ref (A1)	A2	A3	A4
Low complexity	3	0	–	+	+
Performance	4	0	0	–	–
Accuracy	5	0	0	+	+
Compactness	2	0	0	+	+
Total score		0	-3	6	6
Ranking		2	3	1	1
Further development		No	No	Yes	Yes

Criterion	Weight	A1	A2	A3	Ref (A4)
Low complexity	3	–	–	+	0
Performance	4	+	+	0	0
Accuracy	5	–	–	0	0
Compactness	2	–	–	0	0
Total score		-6	-6	3	0
Ranking		3	3	1	2
Further development		No	No	Yes	Yes

Subsystem B: Feed Prepared Wire Lengths

Criterion	Weight	Ref (B1)	B2	B4
Low complexity	1	0	–	+
Performance (feeding speed)	4	0	0	–
Accuracy (precision of feeding)	5	0	–	–
Compactness (physical size)	4	0	0	+
Adaptability (handling of wire sizes and irregularities)	5	0	–	0
Total score		0	-11	-4
Ranking		1	3	2
Further development		Yes	No	Yes

Criterion	Weight	B1	B2	Ref (B4)
Low complexity	1	–	–	0
Performance (feeding speed)	4	+	+	0
Accuracy (precision of feeding)	5	+	+	0
Compactness (physical size)	4	–	–	0
Adaptability (handling of wire sizes and irregularities)	5	+	–	0
Total score		9	-1	0
Ranking		1	2	3
Further development		Yes	No	Yes

Subsystem C: Align Wire Terminal(s) with Insertion Axis

Criterion	Weight	Ref (C1)	C2	C3	C4	C5
Low complexity (aligner & added systems)	2	0	–	+	+	0
Performance (speed)	4	0	0	–	–	–
Reconfigurability	3	0	0	+	+	0
Compactness	5	0	0	+	+	0
Reliability (correct orientation achieved)	5	0	–	+	+	+
Total score		0	-7	11	11	1
Ranking		3	4	1	1	2
Further development		No	No	Yes	Yes	No

Criterion	Weight	C1	C2	C3	Ref (C4)	C5
Low complexity (aligner & added systems)	2	–	–	–	0	–
Performance (speed)	4	+	+	0	0	0
Reconfigurability	3	–	–	0	0	–
Compactness	5	–	–	0	0	–
Reliability (correct orientation achieved)	5	–	–	0	0	–
Total score		-11	-11	-2	0	-15
Ranking		3	3	2	1	4
Further development		No	No	Yes	Yes	No

Subsystem D: Position Wire Along Target Path

Criterion	Weight	Ref (D1)	D4
Low complexity	2	0	—
Performance (speed)	5	0	+
Accuracy	5	0	—
Reliability	4	0	0
Expandability	3	0	—
Load capacity	4	0	0
Total score		0	-5
Ranking		1	2
Further development		Yes	No

Subsystem E: Group, Separate and Retain Routed Wires

Criterion	Weight	Ref (E2)	E3	E4	E5	E6	E7
Low complexity	4	0	0	–	0	0	0
Wire retaining	5	0	+	–	+	+	+
Ease of routing	4	0	0	–	0	–	0
Ease of harness removal	3	0	–	+	–	–	–
Ease of bundling	3	0	+	+	0	+	+
Harness routing flexibility	4	0	+	0	+	+	+
Total score		0	9	-7	6	5	9
Ranking		4	1	5	2	3	1
Further development		No	Yes	No	TBD	Yes	Yes

Criterion	Weight	E2	Ref (E3)	E4	E5	E6	E7
Low complexity	4	0	0	–	0	0	0
Wire retaining	5	–	0	–	0	+	–
Ease of routing	4	0	0	–	–	–	0
Ease of harness removal	3	+	0	+	+	–	+
Ease of bundling	3	–	0	0	–	0	0
Harness routing flexibility	4	–	0	–	0	0	0
Total score		-9	0	-15	-5	-2	-2
Ranking		2	1	5	4	3	2
Further development		No	Yes	No	TBD	Yes	Yes

Subsystem F: Insert Terminal into Connector Housing Cavity

Criterion	Weight	Ref (F2)	F3
Low system complexity	5	0	+
Performance	5	0	0
Accuracy	5	0	0
Compactness	5	0	0
Total score		0	5
Ranking		2	1
Further development		No	Yes

Subsystem G: Store Connector Housing

Criterion	Weight	Ref (G1)	G2	G3	G4
Low complexity	4	0	0	–	–
Reliability	5	0	0	0	–
Precision	3	0	–	+	0
Compactness	4	0	0	–	–
Reconfigurability	2	0	+	+	+
Expandability	2	0	0	0	+
Ease of stocking (insertion)	3	0	+	+	–
Total score		0	2	0	-12
Ranking		2	1	2	3
Further development		Yes	Yes	Yes	No

Criterion	Weight	G1	Ref (G2)	G3	G4
Low complexity	4	0	0	–	–
Reliability	5	0	0	+	–
Precision	3	+	0	+	+
Compactness	4	0	0	–	–
Reconfigurability	2	–	0	0	+
Expandability	2	0	0	0	+
Ease of stocking (insertion)	3	–	0	0	–
Total score		-2	0	0	-8
Ranking		2	1	1	3
Further development		Yes	Yes	Yes	No

Subsystem H: Retrieve and Distribute Connector Housing

Criterion	Weight	Ref (H1)	H2	H3	H5
Low complexity	2	0	–	+	–
Performance (speed)	5	0	+	0	+
Precision	5	0	–	–	0
Compactness	3	0	–	0	–
Reconfigurability	4	0	–	–	0
Robustness	3	0	–	0	–
Total score		0	-11	-7	-2
Ranking		1	4	3	2
Further development		Yes	No	No	Yes

Criterion	Weight	H1	Ref (H2)	H3	H5
Low complexity	2	+	0	+	–
Performance (speed)	5	–	0	–	+
Precision	5	+	0	0	+
Compactness	3	+	0	+	0
Reconfigurability	4	+	0	0	+
Robustness	3	+	0	+	0
Total score		11	0	3	12
Ranking		2	4	3	1
Further development		Yes	No	No	Yes

Subsystem I: Fix Connector Housing

Criterion	Weight	Ref (I1)	I3	I4
Low complexity	3	0	+	+
Ease of fixation	4	0	+	+
Connector flexibility (large/small limitations)	5	0	–	–
Compactness	2	0	+	0
Robustness	2	0	0	–
Total score		0	3	-3
Ranking		2	1	3
Further development		Yes	Yes	No

Criterion	Weight	I1	I3	Ref (I4)
Low complexity	3	–	–	0
Ease of fixation	4	–	0	0
Connector flexibility (large/small limitations)	5	+	+	0
Compactness	2	–	+	0
Robustness	2	+	0	0
Total score		3	6	0
Ranking		2	1	3
Further development		Yes	No	No

G

Iterations of the Morphological Matrix

Subsystem	Subsystem Ideas						
Retrieve wire from wire preparation machine	A1	A2	A3	A4			
Feed prepared wire lengths	B1	B2	B3	B4	B5		
Align wire terminal(s) with insertion axis	C1	C2	C3	C4	C5	C6	
Position wire along target path	D1	D2	D3	D4	D5	D6	
Group, separate and retain routed wires	E1	E2	E3	E4	E5	E6	E7
Insert terminal into connector housing cavity	F1	F2	F3	F4			
Store connector housing	G1	G2	G3	G4	G5		
Retrieve and distribute connector housing	H1	H2	H3	H4	H5	H6	H7
Fix connector housing	I1	I2	I3	I4	I5		

Figure G.1: Morphological matrix showing all generated subsystem ideas

G. Iterations of the Morphological Matrix

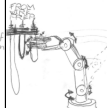
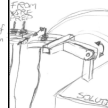
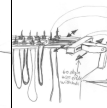
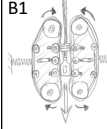
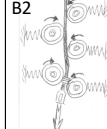
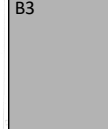
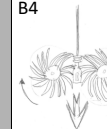
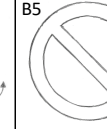
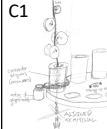
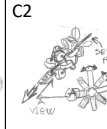
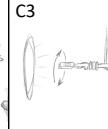
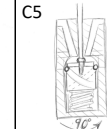
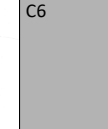
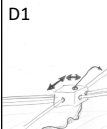
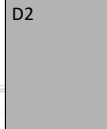
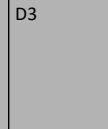
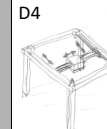
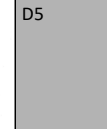
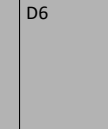
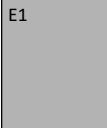
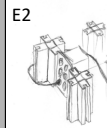
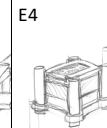
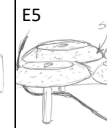
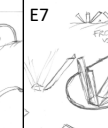
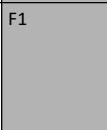
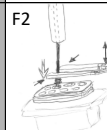
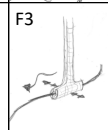
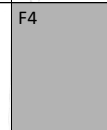
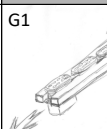
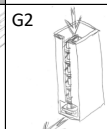
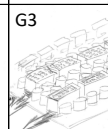
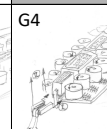
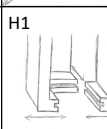
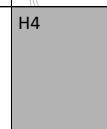
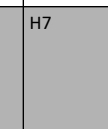
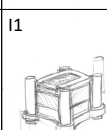
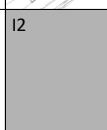
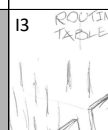
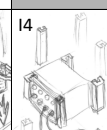
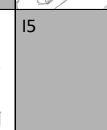
Subsystem	Subsystem Ideas						
Retrieve wire from wire preparation machine	A1 	A2 	A3 	A4 			
Feed prepared wire lengths	B1 	B2 	B3 	B4 	B5 		
Align wire terminal(s) with insertion axis	C1 	C2 	C3 	C4 	C5 	C6 	
Position wire along target path	D1 	D2 	D3 	D4 	D5 	D6 	
Group, separate and retain routed wires	E1 	E2 	E3 	E4 	E5 	E6 	E7 
Insert terminal into connector housing cavity	F1 	F2 	F3 	F4 			
Store connector housing	G1 	G2 	G3 	G4 	G5 		
Retrieve and distribute connector housing	H1 	H2 	H3 	H4 	H5 	H6 	H7 
Fix connector housing	I1 	I2 	I3 	I4 	I5 		

Figure G.2: Remaining subsystem ideas after screening with the elimination matrix

Subsystem	Subsystem Ideas						
Retrieve wire from wire preparation machine	A1	A2	A3	A4			
Feed prepared wire lengths	B1	B2	B3	B4	B5		
Align wire terminal(s) with insertion axis	C1	C2	C3	C4	C5	C6	
Position wire along target path	D1	D2	D3	D4	D5	D6	
Group, separate and retain routed wires	E1	E2	E3	E4	E5	E6	E7
Insert terminal into connector housing cavity	F1	F2	F3	F4			
Store connector housing	G1	G2	G3	G4	G5		
Retrieve and distribute connector housing	H1	H2	H3	H4	H5	H6	H7
Fix connector housing	I1	I2	I3	I4	I5		

Figure G.3: Remaining subsystem ideas after screening with the Pugh matrices



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