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Conceptual Design of a Next-Generation Wire Harness Assembly Workstation for Industry 5.0

A Conceptual Industry 5.0 Workstation at Volvo Cars

Master's thesis in Production Engineering

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Abstract

This thesis presents a conceptual design for the next generation of wire harness assembly workstations at Volvo Cars. With the manufacturing industry shifting toward Industry 5.0, the primary objective of this research was to develop a realistic, efficient, and flexible assembly solution capable of being implemented within a 5 to 10-year timeframe. Through a comprehensive literature review, interviews with industry stakeholders, and a detailed requirement analysis, this study evaluates the integration of Automated Guided Vehicles (AGVs) and collaborative robots (cobots) as a viable strategy to enhance production performance.

The proposed solution emphasizes a gradual transition toward increased automation, where cobots and AGVs are integrated directly into the wire harness workstation to support operators, improve ergonomics, and stabilize material flow. The simulation assessment was used to evaluate the proposed workstation layout, movement sequences, approximate cobot reach, and compatibility with the existing line speed. In addition, the concept includes an AI-based automated quality control system integrated into the wire-harness workstation. The system is intended to support inspection of routing, component presence and variant correctness immediately after assembly tasks are completed.

The findings suggest that the role of the human operator will evolve from performing repetitive manual labor to assuming more high-level responsibilities, such as system management, operational oversight and complex problem-solving. By retaining human expertise for scenarios requiring specialized judgment, the proposed design achieves a balanced synergy between advanced automation and human-centric manufacturing. This research provides a structured roadmap for Volvo Cars to modernize its production facilities, ensuring long-term competitiveness and operational efficiency.

Keywords: Assembly, Wire Harness, Automation, Simulation, AGV, Cobots

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John Carlsson, Arvind Navin Sekar Vasanthi, Gothenburg, June 2026

List of Acronyms

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

AGV	Automated Guided Vehicle
AI	Artificial Intelligence
AMR	Autonomous Mobile Robot
AR	Augmented Reality
CNN	Convolutional Neural Network
CV	Computer Vision
DL	Deep Learning
DLO	Deformable Linear Objects
HRC	Human-Robot Collaboration
IIoT	Industrial Internet of Things
IoT	Internet of Things
JIS	Just in Sequence
JIT	Just in Time
KPI	Key Performance Indicator
LiDAR	Light Detection and Ranging
LoA	Level of Automation
MES	Manufacturing Execution System
MPS	Modular Production System
MSD	musculoskeletal disorders
ML	Machine Learning
NNA	Non-Value-Adding
NNVA	Necessary but Non-Value-Adding
OIS	Operator Instruction Sheet
SQC	Statistical Quality Control
VA	Value-Adding
VR	Virtual Reality
WES	Work Execution Sheet
QA	Quality Assurance
QC	Quality Control

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1

Introduction

The introduction chapter provides an overview of the topic and establishes the context for the thesis. It outlines the motivation for the study, the industrial relevance and the challenges that motivate the development of future concepts for harness assembly.

1.1 Background

Vehicle manufacturing has become significantly more complex in recent years due to shorter product life cycles, rapidly increasing model variants and the shift toward mass customization and personalization [13]. Modern automotive plants must handle a wider range of options and technologies than ever before, which places pressure on assembly systems. This rise in product variety increases operational complexity, reduces predictability and demands more flexible production processes. The transition from traditional mass production toward mass customization fundamentally reshapes manufacturing, requiring new approaches to assembly system design and flexibility within the workstation.

Automation in manufacturing is evolving from predefined systems toward smart, adaptive, automated and human-centric technologies. This development creates new requirements for how future workstations are designed. As aforementioned, this shift is driven by the need for more flexibility and responsiveness to manage a more personalized production. However, the introduction of advanced automation also increases the complexity of managing manufacturing systems, requiring careful integration of human factors, supervision and system adaptability. As [39] highlights, modern automation technologies can enhance productivity but simultaneously demand new approaches to balancing automated functions with operator roles. Technological development is making manufacturing processes increasingly complex, which in turn places new demands on companies' management practices, operational processes and the competencies of their personnel. Organizations that are good and efficient at adopting and utilizing new technologies are generally better positioned to succeed in emerging and competitive markets[34].

Industry 4.0 introduced cyber-physical systems, IoT connectivity and data-driven automation, enabling more intelligent and connected production environments. While these technologies can improve efficiency and transparency, they also make the systems more complex and require new competencies. Industry 5.0 builds on this

foundation by emphasizing human-centricity, resilience and sustainability. It shifts the focus from pure automation to meaningful collaboration between humans and intelligent systems, aiming to enhance workers' creativity rather than replacing them [44].

Ergonomics plays a critical role in modern manufacturing, particularly in manual assembly environments where repetitive motions and awkward postures are commonly involved in assembly tasks. Unfavourable ergonomic conditions are associated with musculoskeletal disorders, reduced productivity and increased sick leave. As explained by [43], asymmetrical and physically demanding assembly movements increase ergonomic risk and contribute to long-term health issues and societal costs that can be mitigated through improved workstation design. Harness assembly is a physically demanding task in car production. Operators must route and secure large cable bundles inside the vehicle body, often in tight spaces and awkward positions. This aligns with what has been learned at the shop floor. During initial discussions at Volvo Cars, several operators expressed recurring back discomfort and strain in their wrists and fingers associated with the harness installation tasks.

The structure of the thesis follows a logical progression from identifying the problem, collecting empirical data, deriving requirements, developing and evaluating concepts, assessing the selected solution through simulation and finally discussing how these results answer the research questions.

1.2 Aim

The aim of this thesis is to develop a conceptual design for a next-generation wire harness assembly workstation at Volvo Cars. New technologies will be evaluated and result in clear recommendations that can be implemented in the factory in the future.

1.3 Objectives

- Identify future requirements for the station by analyzing expected technological developments and organizational needs
- Find out which future automation technologies could realistically be integrated into the station in the future
- Deliver a final recommended concept that Volvo Cars can implement in the plant and that remains compatible with expected technological developments over the next five to ten years.

The objectives presented above define the overall direction and purpose of the study. To further structure the investigation and provide a clear framework for the analysis, these objectives were translated into a set of research questions. The following

research questions therefore guide the thesis work and support the achievement of the stated objectives.

- Which future technologies could realistically be integrated into the station?
- What requirements must the future station fulfill?
- What concept is recommended for the next 5–10 years?

1.4 Limitations

The main limitation of this project is the time horizon. The proposed workstation concept is constrained to technologies and methods that can be useful in the upcoming period of five to ten years into the future. Conceptual or experimental solutions beyond a five-year maturity horizon are therefore excluded in this thesis.

This thesis does not focus on the entire assembly line. Instead, the scope is limited to the wire harness assembly workstation and upstream and downstream processes are not analyzed unless the proposed changes to the harness station are expected to have a direct impact on other stations. It is also important to note that the objective of this thesis is not primarily to identify improvement potential to the current workstation or to solve existing problems, but rather to define a potential future state for the wire harness workstation. The study is limited to a single wire harness station at Volvo Cars, which may reduce the direct generalizability of the results to other processes or manufacturing systems.

The selected process, wire harness assembly, is highly sequence-dependent and involves handling a deformable object with complex and unpredictable geometry. While full robotic manipulation of the entire harness may become more technically achievable within the next 5–10 years, current vision and simulation tools are still limited in their ability to accurately track, predict and model the real-time behavior of flexible cables. As a result, the thesis cannot fully assess a complete automation scenario using today's software capabilities. Instead, the proposed concept outlines a future workstation designed to accommodate increasing levels of automation as these technologies mature, while acknowledging that current simulation environments cannot yet replicate the physical behavior of deformable linear objects perfectly.

Cost calculations are not included in this thesis. The primary aim of the study is to explore future technologies and evaluate their feasibility for wire harness assembly in the long term. Since many of the technologies considered are still emerging, their cost structures are highly uncertain and expected to change significantly as development progresses, suppliers mature and larger scale production becomes possible. Also, estimating installation effort and cost for the proposed future station is outside the scope of this thesis. Cost estimates for technologies at this early stage would

be speculative and risk misrepresenting their true economic potential. For this reason, the evaluation focuses on technical feasibility, ergonomic impact and alignment with future requirements, rather than on cost-based comparisons. This limitation is particularly important because the interview findings showed that economic performance, including return on investment and payback time, is an important consideration when evaluating new production solutions at Volvo Cars. Since no cost or investment analysis was conducted, the study cannot determine whether the proposed concept provides a positive business case or meets the payback expectations identified in the interviews.

2

Theory

This theory chapter provides the basic foundation needed to establish a relevant basis for processing, analyzing and discussing the research questions that are presented later in the study.

2.1 Industrial revolutions

The industrial revolutions can be understood as successive periods of technological transformation, each marked by characteristic innovations and shifts in production systems. These periods represent a cross-section of major technological breakthroughs and the milestones that reshaped the industry[28]. The three early industrial revolutions all represented significant shifts in production. The first revolution was about the introduction of the steam engine. Then the second followed with the introduction of using electric power and the third was about introducing IT and automation into the industry[18]. Most relevant for today's manufacturing are the fourth and emerging fifth industrial revolutions, which will be presented in the following sections.

2.1.1 Industry 4.0

Industry 4.0 represents the fourth industrial revolution and is characterized by the integration of technologies such as the Internet, artificial intelligence (AI) and digitalization [36]. It is transforming manufacturing by enabling increasingly connected, automated and data-driven production systems [34]. The expression was first used in 2011 and it described the upcoming era of integrating and adapting to the new technologies in the manufacturing industry[18]. AI refers to algorithm-based systems that can perform tasks commonly associated with human intelligence [36]. Using AI has been promising in the application of predictive maintenance, predictive analytics, material flow and managing the supply chain. Machine learning is a subset of AI that uses data and algorithms to make more accurate predictions. Machine Learning (ML) focuses on developing algorithms that learn from data without programming. Deep Learning (DL) is a further extension of ML through deep neural architectures capable of feature extraction. Computer Vision (CV) lies at the intersection of AI and ML, enabling machines to interpret and analyze visual information such as images and video[8]. Big data refers to large volumes of data characterized by variety, velocity and volume, commonly referred to as the three Vs. Big data analytics are used to find patterns of information and find how the

data behaves. Internet of things (IoT) and industrial internet of things (IIoT) where "things" refer to physical objects with sensors and with the help of digital technologies can connect and communicate with each other. IoT sensors should enable a system to behave more efficiently and smart which is important in Industry 4.0 and the potential of IoT in the industry in the future is huge. As more companies are adapting to Industry 4.0 more of their systems are getting connected to the Internet, which in turn increases the risk of getting exposed. Cyber security is the solution to these digital attacks. These technologies are all part of what belongs in the theory of Industry 4.0. Automation and robotics go hand in hand as their purpose is to improve productivity in the production. Even if automation and robotics have been used in industries for many decades, the robots that would be used in Industry 4.0 environment would have more advanced sensors, data communication channels, navigation and guidance systems and also better data processing abilities

However, Industry 4.0 technologies also come with what can be seen as drawbacks. Earlier generations of robots mainly performed heavy, repetitive tasks, supporting workers without replacing them entirely. The real concern with Industry 4.0 lies in the rapid development of artificial intelligence (AI). Unlike traditional automation, AI has the capability to solve complex problems autonomously and also to perform tasks that were previously limited to humans. As AI and automation continue to advance, studies suggest that up to 80 percent of jobs in medium- and low-income sectors could be at risk of automation[36].

The future technologies described above significantly impact how assembly workstations are designed. The entire assembly workstation system will be heavily affected and changed by these emerging technologies in terms of connectivity and communication[18]. This is supposed to improve agility, ergonomic factors and also make the operations at the workstations more cost effective.

2.1.2 Industry 5.0

The shift from Industry 4.0 to Industry 5.0 means that the heavy focus on automation will turn into a more human-centric approach[44]. One of the important aspects of Industry 5.0 is that human creativity still should coexist with advanced technologies and not be replaced. In industry 5.0 systems should enhance rather than replace human intelligence and empathy. One of the objectives with Industry 5.0 is to enable human-machine collaboration. It consists of technologies such as AI, collaborative robots, human digital twins and augmented reality (AR) and virtual reality (VR) platforms to enhance human performance on the shop floor. These technologies are being deployed to not just improve productivity, but also equally as important to enhance inclusivity and keep human beings central.

Industry 4.0 focused on using smart manufacturing technologies to increase automation and reduce manual labor, whereas Industry 5.0 emphasizes customization and a shift toward humans taking on more skilled roles while working alongside intelligent machines[20]. In this new era of manufacturing, a common human task is to guide

or supervise robots rather than perform repetitive manual work. Industry 5.0 therefore establishes a more integrated relationship between humans and collaborative robots, moving beyond the Industry 4.0 view of simply deploying robots as isolated automation tools.

Enabling technologies in Industry 5.0 include networked sensor-data interoperability, multiscale simulation and dynamic modeling, production tracking, virtual training, autonomous systems and advanced machine cognition, all of which support the shift toward more intelligent and customized manufacturing[20].

2.2 Automation

Automation can be understood as a set of technologies that enable machine operations and system-level processes to be performed with minimal human intervention[28]. In industrial settings, this reduces manual workload, increases process stability and supports higher productivity. Manufacturing companies that have a strong competence in adopting new technologies and automation solutions are more likely to be very successful, while those that are slow to adapt often struggle to remain competitive[34].

2.2.1 Human Robot Collaboration (HRC)

In the industry today it is clear that collaboration between humans and robots is highly central and it is one of the most promising new technologies[15]. Operators have experienced a clear shift in their role from being the ones performing all tasks manually to increasingly collaborating with new technologies and utilizing them as effectively as possible[34]. Robot - human collaboration (HRC) is used to meet the increased variety of products and the wide range of options available to consumers place significant demands on modern production systems[15]. The main point of introducing HRC is that the strength of both humans and robots can be combined which can be helpful in several industrial settings including assembly tasks. In a successful HRC setting, humans and robots share their skills and perform their tasks next to each other in the same work area. This type of collaboration between human operators and robots enables assembly stations to be more flexible and allows the production process to perform and produce more customized products. HRC is capable of minimizing the heavy and repetitive workload for the human at the same time as the human involvement can enhance the robot's applicability by providing improved understanding and dexterity that robots alone may lack.

2.2.2 Safety Considerations: Collaborative vs. Industrial Robots

Cobotics, stands for “collaborative robotics” and it is an emerging area and is important for the fifth industrial revolution[31]. A cobot refers to robots that are designed to work alongside human operators. Cobots are designed with safety functions that can support operation alongside humans, although safe operation depends on the

complete application and its risk assessment[44]. Figure 2.1 illustrates a typical collaborative setup in which a human operator and a cobot work within a shared interaction zone. Cobots are designed with features that can enable collaborative operation with human operators. However, safe operation depends on the complete application, including the robot, end-effector, payload, operating speed, task and surrounding working environment. The example highlights how cobots are designed to operate in close proximity to humans in applications where the risk assessment and implemented safeguarding permit collaborative operation.

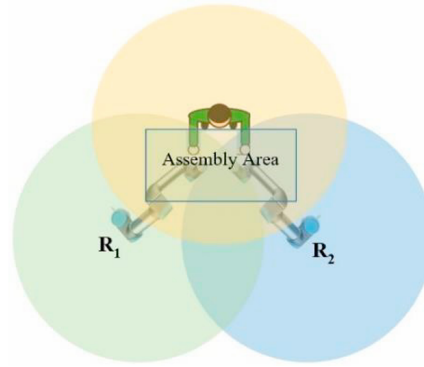


Figure 2.1: Collaborative setup in which a human and a cobot work within a shared interaction zone.

The things that differ a cobot from industrial robots is that cobots are equipped with sensors and safety equipment that should make them capable of working with humans and enables teamwork between humans and machines[31]. Industrial robots, on the other hand, often need safety barriers that hinder humans from being near robots, since they are too dangerous. Table 2.1 provides an overview of the key differences between collaborative robots and traditional industrial robots, particularly in terms of safety and interaction with human operators as described by [31]. This distinction is fundamental for understanding why cobots are increasingly relevant in human-centric assembly environments.

Table 2.1: Summary of key differences between industrial robots and collaborative robots (cobots) in terms of HRC.

Industrial Robot	Cobot
Optimized for repetitive, high-volume tasks	Designed to work alongside people
Needs to operate in isolated cells due to safety risks	Built-in sensors and force limits
Can handle heavy parts and tools	Prioritizes safety over speed
Most ideal for stable, high-volume processes	Better for small batches and frequent changes

2.2.3 Safety in HRC

Despite ongoing technological progress, it is still common for production companies to experience internal conflicts between maintaining human safety and maximizing production output. This is why it is important to develop approaches that balance safety requirements with efficient production practices[34].

In traditional industrial-robot applications, risk mitigation is relatively straightforward. Because it is difficult to eliminate risks when humans are present, the standard approach is to isolate the robot and remove human access to hazardous areas. Mechanical risks are essentially reduced to zero by using physical safeguards, fencing and by ensuring that humans are never located within the robot's operating space[10].

Safety for collaborative robots, however, is more complex and more interesting, as humans and robots intentionally share the same workspace. In these environments, risk situations are generally more probable but less severe compared to industrial robots, since unexpected human-robot contact is allowed under controlled conditions. The most detailed safety standard for collaborative robots is ISO TS 15066[10], released in 2016, which specifies requirements for safe human-robot collaboration. In short, the standard defines four methods for achieving safe HRC:

- Safety-rated monitored stop — the robot stops its motion and movements when an operator enters the collaborative workspace.
- Hand-guiding — the operator can directly control the robot's motion with their hands at a safe and limited speed.
- Speed and separation monitoring — the robot's control system continuously monitors the relative speed and distance between the robot and the operator.
- Power and force limiting — the robot's design limits the forces and power it can exert, allowing small, non-harmful contacts with humans.

2.2.4 Level of Automation

Level of Automation can be described as the degree to which tasks are planned and carried out by machines rather than humans[5]. The level of Automation is not black or white. There are different grades between full automation and fully manual work.

Table 2.2: Riley’s Levels of Automation, illustrating how decision-making and task execution gradually shift from human operators to automated systems [2].

Automation Level	Description
Level 1	Manual operations
Level 2	Processing of available information
Level 3	The system cannot perform any action by itself, unless it advises the operator
Level 4	Recommendations: The machine has no power to act and is limited to communication with the operator
Level 5	Recommendations with interaction: The machine does not have the power to act and is limited to communication with the operator
Level 6	Adaptive recommendations: The machine has no power to act and is limited to communication with the operator
Level 7	The machine is a servant and has the possibility to perform actions
Level 8	The machine is an assistant and can perform actions but requires operator approval
Level 9	The machine is associated and can perform actions autonomously without explicit authorization, but the operator can always replace it
Level 10	The machine is a partner and has the same rights as the operator
Level 11	The machine is a supervisor and can replace the operator who has no authority
Level 12	Fully autonomous operation

2.3 Deformable Linear Objects and Automating it

Deformable linear objects (DLOs) refer to objects such as wires, ropes and cables. They are used in a wide variety of applications, including both medical and industrial environments[7]. The term linear reflects that their length greatly exceeds their cross-sectional dimensions, while deformable refers to the fact that their shape changes under external forces and during movement and use. In manufacturing industries such as automotive and aerospace, DLOs appear in the form of electrical cables, wiring harnesses and hose bundles. Despite their frequent use across several industries and especially in automotive assembly station. It has been shown to be difficult and challenging for robots to manipulate these cables effectively and, in particular, quickly. Their deformability and flexibility make it very hard for robots

to handle them accurately. Also the DLOs have non-rigid parts which results in additional degrees of freedom that affects the ability of cobots to handle them easily. In general, a part or component can be considered non-rigid if it can be deformed by more than one of its own dimensions when subjected to external forces.[22].

2.4 Lean principles in Assembly Stations

Lean is introduced as a production philosophy grounded in The Toyota Way, where the central focus is on eliminating waste and creating value through efficient, stable and continuously improving processes. It builds on the idea that every activity in a production system should contribute directly to customer value, and anything that does not is considered waste to be removed[17].

2.4.1 Andon

Andon was first introduced in the middle of the 20th century. Its main purpose was to draw attention to problems and to suspend the assembly line when issues occurred, such as quality problems, not finishing a task on time or other interruptions to the process[29]. An Andon system typically consists of a button or a pull cord that the operator can activate when an issue arises that requires the line to stop. When the operator pulls the cord, a light next to the station turns on, indicating that a team leader or supervisor should come to the station and help solve the problem.

In the past, Andon has simply been a light and a signal that was either on or off, but it has developed over the years. Today, the system is more advanced and often includes an Andon board next to the station to make issues more visible. These boards can show information such as breakdown time and the type of issue. The system increases visibility in the production and helps operators and team leaders react quicker when problems occur[29].

2.4.2 Takt time

Takt time expresses the maximum allowable time to produce one unit if the line is to meet demand. It is not a measure of how fast the process currently runs, but the target pace the system must achieve[17]. The formula for calculating the takt time for a station is as follows:

$$\text{Takt Time} = \frac{\text{Available Production Time}}{\text{Customer Demand}}$$

2.4.3 Just in time

Material supply plays a critical role in assembly systems, as it ensures that components are available at the right time, in the right quantity and are readily accessible. Just-in-time means supplying each downstream step in production with exactly what

it needs, exactly when it is needed and in the required quantity. This principle is built on consumption-driven replenishment, where material moves only when a part has been used, rather than pushed forward based on forecasts[17].

2.4.4 Just in Sequence

In the automotive industry, just-in-sequence is the most commonly used method for supplying materials to assembly stations[12]. The assembly sequence of vehicles is determined several days before production and then communicated to suppliers so that the components are in the correct sequence. Multiple variants with a wide range of options are assembled, creating a need for different components for each individual car. In modern assembly systems, this method is increasingly supported by technologies such as automated delivery vehicles. Smart automation can be implemented and increase efficiency and flexibility at the station[46].

2.5 Future Technologies for Harness Assembly

This section presents future technologies that could be relevant in the future for a harness assembly station. The purpose is to describe the capabilities, limitations and potential contributions of each technology in a final assembly environment. These descriptions form a foundation for evaluating which technologies may be suitable for the future wire harness station.

2.5.1 Humanoid Robots

A humanoid is a robot designed with a human-like form, typically including a head, arms, fingers and legs. Development of human-like robots has been ongoing since the 1960s. The purpose of developing humanoid robots is to mimic real human behavior and human physical characteristics [47]. What researchers aim to achieve with humanoid robots in manufacturing is the ability for them to perform tasks that are normally carried out by humans. Recent breakthroughs in humanoid robotics have largely been driven by developments and innovations in AI, sensor technology and computer technology. In their current state, humanoid robots are able to interact with humans and can behave and move in ways that are fairly similar to human motion. They can interact and cooperate with human workers and can enhance human work in various tasks. For a humanoid robot to work well and efficiently alongside humans and to perform tasks accurately, it requires high-performing sensors and actuators. The control system is the core of the humanoid robot, as it enables the robot to understand the environment in which it operates and to interpret the presence and actions of the humans around it[47].

Humanoid robots are more adaptable than industrial robots. The development of humanoids has recently moved from the research stage towards real-world applications, driven by pioneers such as Tesla's Optimus and Boston Dynamics' Atlas[16]. The integration of reinforcement learning, imitation learning and multi-modal interaction has provided humanoid robots with autonomous adaptation and human-collaboration

capabilities. Both Tesla and Honda are currently testing humanoid robots in assembly-task operations as well as in logistics tasks [16].

However, there are significant challenges that hinder humanoids from being employed in environments that require high flexibility and adaptability, such as a complex assembly station. There are gaps in the development of humanoids that limit their performance, and these issues prevent them from being more widely used in assembly tasks. This is especially true for tasks that require high precision, where the control system becomes a major limiting factor. As mentioned by [16], there are currently delays between the perception, decision-making and control modules, which affect overall performance. There are also difficulties in enabling humanoids to walk in complex terrain and in achieving reliable self-collision avoidance. The motion-control precision is insufficient to meet the demands of fine operations and the robustness under external disturbances is inadequate. There are also challenges related to perception and cognition. These include issues with precision and coverage range, as well as difficulties in multi-sensor fusion. Instability in dynamic environments remains a problem despite recent advancements in deep learning.

The ongoing development of AI is of great importance, together with technologies such as deep learning and image processing. These technologies help and enable humanoid robots to position themselves accurately in order to carry out high-precision tasks and to recognize functions [47].

Based on the identified challenges by [16], several key research and development directions have been highlighted for advancing humanoid robot capabilities. The most relevant future needs include:

Collaborative intelligence and multi-robot systems: Development of coordinated multi-robot frameworks, knowledge-sharing and hybrid virtual-physical collaboration using digital-twin technology.

Enhancement of autonomy and intelligence: Integration of meta-learning, causal reasoning and large language models to improve decision-making, task adaptation and performance in uncertain environments.

Environmental adaptation capabilities: Advances in sensor perception, adaptive motion control and bio-inspired algorithms to enable stable operation in complex and dynamic environments.

Technical infrastructure and cost reduction: Progress in flexible electronic skin, soft robotics, integrated actuator designs and improved energy management to enhance performance while lowering system cost and enabling scalable production.

2.5.2 Exoskeletons

Exoskeletons are an emerging technology designed to improve work for operators and primarily to reduce injury risks, especially musculoskeletal disorders (MSDs)[33]. The lumbar spine is the most affected body region in manual manufacturing. Exoskeletons have been viewed as a helpful tool for reducing issues related to this

area[35]. Their purpose is to support the body during physically demanding tasks, thereby lowering strain and decreasing the risk of musculoskeletal problems. Exoskeletons are worn on the body and support ergonomics by externally strengthening the body[33]. Exoskeletons can be designed as active systems, meaning they are actuated and provide powered assistance to the user during movement. In contrast, passive exoskeletons rely entirely on elastic or mechanical components, offering support without any external power source [4]. Passive exoskeletons offer advantages such as their lower cost and reduced technical complexity, which makes them more accessible for industrial deployment in a larger scale. Their primary function is to reduce the operator’s physical workload by supporting specific muscle groups during demanding tasks, such as lifting or holding loads in static or awkward positions. Despite current automation trends, manual work remains important, and this is where exoskeletons can provide valuable support[33].

A research study [33] found that when used appropriately, exoskeletons can reduce muscular activity in the targeted muscle, both at peak levels and on average. The magnitude of this effect varies depending on the situation in which the exoskeleton is used, its suitability for the specific task, and the characteristics of the exoskeleton itself.

The study by [33] also showed that exoskeletons do not provide full support throughout the full range of tasks. When it comes to supporting the back, exoskeletons are most useful in the lower range of the lift. During the tests carried out on assembly tasks, exoskeletons support the shoulders mostly when working above head level. They can reduce or slow down the effects of muscular fatigue.

Several studies referenced in [4] show that passive exoskeletons have been successful in lowering muscular fatigue, particularly in the muscles they are designed to support. Workers also reported a lower perceived workload, indicating that the assistance provided by the exoskeletons is noticeable and meaningful during physically demanding operations.

Another problem in the case of exoskeletons is the “one-size-fits-all” approach, which is often used for cost-effectiveness in manufacturing. Most exoskeletons are produced in standardized sizes and configurations, which makes them cheaper to develop and distribute, but this also limits how well they fit individual users[35]. There is very little research on user-adapted or personalized exoskeletons, even though such adaptation is necessary for the technology to function optimally. For an exoskeleton to work as intended, it must be wearable and it should fit the user’s body, movements and working conditions. Without this level of adaptation, comfort and usability are compromised.

2.5.3 Human-Centric Cobots

Collaborative robots can ease the work for humans in the assembly station or along the assembly line. These robots have collision sensors and are designed with force

limits that can contribute to reducing risks during operation near human workers [14]. In addition to this, they are cost-effective and flexible, while also contributing to improved quality and productivity. They have a compact size that allows them to be used even when floor space is limited, and they are well suited for environments where space efficiency is important. Collaborative robots help manufacturers take over labor-intensive tasks such as picking parts, loading machines and carrying out quality checks. These activities are hard for human operators to perform with consistent accuracy over long periods of time. Because of these characteristics, collaborative robots are valuable and relevant components in smart-factory technologies[14]. Compared to industrial robots, cobots have much lower requirements for programming. They can be set up and adjusted more easily, which reduces the need for specialized programming expertise. Cobots operate at lower speeds than traditional industrial robots, typically reaching only one-third to one-half of their performance. This reduced speed is part of their design as they are prioritizing safe interaction with human operators ahead of higher speed. A cobot should therefore not be considered inherently safe. Safety depends on how the complete application is implemented, configured and integrated into the workstation. [19].

Numerous studies have applied cobots to address productivity and ergonomics challenges in manufacturing, creating large and promising opportunities for improved performance. With the development of Industry 4.0, it has become increasingly important that cobots can deliver what consumers and production systems require in a timely and efficient manner without any sort of disruptions. Cobots have contributed to greater production flexibility, as they can be quickly adjusted to different tasks and changing demands. Because of their safety features and their ability to work directly alongside human operators, cobots have become one of the fastest-growing segments of the robotics market[19].

It has also been a research project in which the integration of Festo's modular production system (MPS) with Universal Robot's UR5 manipulator was attempted, where simple pick-and-place operations were performed using color recognition and basic object identification. These experiments demonstrated how a cobot can interact with modular training equipment[19].

Other technologies that has been tested together with cobots are deep-learning-based cameras and advanced image-sensor systems[19]. They have been widely used and integrated in different cobot setups to support efficient, safe and comfortable collaboration between robots and humans working in the same workspace. With the continuous development of artificial intelligence, cobot capabilities have advanced fast and this has been seen in shared work environments where adaptability and perception are essential. In addition, cobots offer relatively low system-integration costs[19].

As aforementioned there is considerable ongoing research in relation to cobots. One of the main things in the development of future cobots is how to integrate AI. As AI continues to develop, cobots gain the ability to think, adapt and make judgments

based on real-time data[19]. This increased intelligence reduces the need for humans to act as the constant decision-makers, allowing the robot to handle more complex or variable situations autonomously. In future applications, cobots may also be combined with automated guided vehicles (AGVs) to form hybrid mobile-manipulator systems. By integrating a cobot with an AGV platform[19], the robot is no longer restricted to a single workstation or task but can move more freely across the production environment. Successful cases already demonstrate how such systems can perform material handling, inspection and assembly tasks with greater flexibility. When combined with autonomous mobile robots (AMRs), the robotic arm is often implemented as a cobot to support collaborative interaction with humans while maintaining high adaptability. This integration increases mobility, expands the range of possible tasks and supports more dynamic production layouts[19]. Cobot arms, compliant grippers and mobile platforms with collision-avoidance functions are shifting robots from enclosed work cells to production lines and other operational areas. At the same time, advances in sensors and deep-learning technologies are enabling new automation applications that were previously difficult to implement. Looking ahead, the development is promising, as collaborative robots increasingly rely on AI and machine learning to speed up operations by optimizing route choices in real time[14].

2.5.4 Full Automation

Advances in factory automation that has taken place during the last years have led to significant improvements in both manufacturing quality and productivity. However, many manufacturing processes that involve non-rigid parts are still not as fully automated as those designed for rigid components [22]. Furthermore, intensified research and development regarding the development of computer vision, robotics and artificial intelligence is expected and will significantly affect the future of assembly stations. The growing interest in automating factory floor workstations, rather than relying on manual human labor, can partly be attributed to the increasing cost of human labor. At the same time, the cost of technologies such as various types of industrial and collaborative robots has decreased, making automation a more economically attractive alternative.

A study conducted at Mercedes-Benz concluded that there are currently three major factors that make automation of wire-harness assembly onto the car body particularly challenging. These are[22]:

- Complex supply chains, which introduce variability and coordination difficulties.
- A lack of automation-friendly product design, especially regarding high-voltage connectors and their geometries
- The need to adapt manufacturing processes to handle deformable components in a way that still complies with industrial requirements.

Gripper design plays a crucial role in successful grasping operations and in handling deformable objects. Recent progress in machine-learning methods has improved

real-time understanding of DLO behavior, but there is still a considerable distance to go before these solutions are ready for large-scale industrial use. With greater dexterity and more advanced cognitive capabilities, the gap between automation for rigid objects and automation for non-rigid objects will likely be bridged in the future[22].

2.5.5 Vision-Guiding

One of the most common solution for automating the wire harness assembly tasks are with the use of a robot arm. For a robot arm to function correctly it needs to be good at target detection and localizing its surroundings. That is the reason why robots needs integration of a vision-based system and 3D camera. The robot arm needs to recognize branches within the wire harness and be guided through the sometimes disordered wires. Attempts have been made to use collaboration between human and robot to successfully carry out the task, but full automation has not been reached without the use of vision guiding. Detecting the wires has been possible with the use of convolutional neural networks (CNN) and a depth camera. Detecting different wire harness branches is a difficult task but with the help of using differences in color of each of the branches, it is possible to efficiently detect each wire branch[27].

Using computer vision can be revolutionizing in the aspect of automation DLO assembly tasks. Object detection will be highly valuable in future applications, for example by enabling a system to recognize clamps so that a robot arm can reach, grasp and manipulate them [42]. Adding markers to the objects can simplify detection and recognition and improve reliability [22]. The use of CNNs and recent advances in deep learning for computer vision make it possible to achieve efficient detection and allow the robot arm to handle the objects with better accuracy through improved image-based perception[42].

2.5.6 Industrial Robots

Large manufacturers have benefited from automation for decades by adopting traditional industrial robots. These robots were built for high-volume production and for performing standardized tasks with very low variability. They were expensive systems designed to operate without humans in close proximity, and their purpose was to execute repetitive, predictable operations at scale [14]. Because of this, traditional industrial robots became central to mass-production environments where consistency, speed and uniformity has been required.

A study that has looked at harness assembly [38] presents an automated connector mating method developed for printed circuit board assembly, not automotive applications. The researchers designed a connector-feeding system that aligns connectors so the robot can grasp them in a stable and repeatable way. An eye-in-hand camera is then used for vision-based tracking, allowing the robot to correct large position errors before insertion. During the mating phase, the robot applies a tilt strategy

combined with impedance (force) control. This enables compliant motion, safe contact forces and automatic compensation of small misalignment which is critical for the very tight assembly tolerance of 0.2 mm. The system achieved a 92 percent overall success rate (46 out of 50 trials), with failures mainly caused by improperly grasped or slightly bent connectors. Although the experiments were performed on PCB connectors using industrial robots, the methodology is highly relevant to automotive wire-harness assembly. Car connectors also require precise alignment, a more robust gripping procedure and vision-based positioning. However, the findings cannot be directly transferred to automotive wire harness installation. The PCB study focused on connector mating in a controlled and structured environment, whereas automotive wire harness assembly involves flexible and deformable cables, larger spatial variations, constrained vehicle geometries and a continuously moving production line. The reported success rate therefore demonstrates the potential of combining vision and force control for connector mating, but does not demonstrate that the same performance can be achieved for complete automotive wire harness installation. Further development and testing under representative automotive conditions would be required.

2.6 Automated Transport Solutions

2.6.1 Automated Guided Vehicle

An Automated Guided Vehicle (AGV) is a driverless vehicle that is used to transport materials within factories, warehouses or distribution centers[45]. It had its first application in the automotive industry during the 1950s[46]. It is capable of moving goods safely and efficiently without a human driver[45]. AGVs are commonly used to handle heavy loads, support internal logistics and streamline material flow in controlled industrial environments. AGVs are often seen as an enabler of industry 4.0 and it is also a very efficient tool in increasing the flexibility in the internal logistics. During the last years AGV has been replacing the human workforce a lot inside factories and carries out more and more of the transportation without humans. AGVs can increase productivity and support compliance with takt time because their flexibility enables reliable material delivery.

AGVs has had two main applications in the automotive industry. The first one is material handling where AGV functions as tool to transport material in a warehouse setting[46]. It can supply material and components to the right position and has been used to deliver and also to dispose material. The other application is in the production environment in assembly operations and mostly as a platform for final assembly.

2.6.2 Autonomous Mobile Robots

During recent years rapid developments in driverless transportation has taken place, especially regarding sensors and robotic controls and Autonomous Mobile Robots (AMRs) has been seen as an upcoming and promising technology that can be a

useful addition in the future of manufacturing[46]. AMRs are equipped with Light Detection and Ranging (LiDAR) sensors and vision cameras that helps AMRs to become a new form of AGV technology for material handling tasks. AMRs are also, in contrast to AGVs driving autonomously which means that they do not have a predefined path that it travels along. The help of the improved sensors and typical Industry 4.0 technologies such as Internet of Things (IoT), Big Data, Machine Learning and AI has enabled the AMRs to self-define the best or most efficient path based on the starting and end positions that it has been given. Another advantage with AMRs is that the sensors enable them to in real time change transport route based on obstacles that might be in its way. This enables them to work closely to human workers and other machines without danger. If the production conditions changes, AMRs can quickly find a new route to drive and still be able to do the tasks which is very valuable in dynamic market environments.

2.7 Quality

2.7.1 Quality Assurance

Quality assurance (QA) in manufacturing refers to the systematic follow-up of quality characteristics in a component to identify potential defects[25]. The word assurance is often used to describe something that is giving confidence or the act of making certain[3]. QA therefore includes activities within the quality system that provide confidence that a product or service will fulfill specified quality requirements. This is important both internally to gain confidence that quality is correct but also for the customers. Traditionally, this work has been performed by human experts, which often leads to delays and interruptions in the production flow. As manufacturing systems evolve, AI technologies offer new opportunities to support QA activities by enabling automated, online condition monitoring[25]. A definition is provided in [3], stating that “all the planned and systematic activities implemented within the quality system that can be demonstrated to provide confidence that a product or service will fulfill requirements for quality”.

2.7.2 Quality Control

Quality Control (QC) focuses on evaluating a process and determining what corrective actions are needed to keep it stable. QC is about ensuring that a process produces predictable and consistent results. A process is considered in control when the variation in its output comes only from normal, inherent causes rather than from irregular or assignable disturbances. The purpose of QC activities is therefore to verify that quality requirements are met and to intervene when the process deviates from its expected performance.[3]. One definition for quality control is: the operational techniques and activities used to fulfill quality requirements.

2.7.3 Automated Quality Control

In the manufacturing industry today, producing products with the right quality is integral to all companies. In assembly stations that often are mostly manual the quality is controlled by humans. Oftentimes the method used is something called quality inspection which is the process of examining, measuring and testing a product or process to make sure it meets the required standards before the product moves to the next production stage or reaches the customer [21]. Manual inspection is time-consuming, prone to human error and inconsistent across long production runs. These limitations make it difficult to maintain stable quality levels when relying solely on human judgment. Traditional computer vision methods also fall short, as they lack the ability to learn and improve over time, which restricts their effectiveness in more complex or variable inspection tasks [30]. Automation of quality inspection reduces the need for skilled quality workers, since many of the manual judgment-based tasks are taken over by automated systems. By relying on automated inspection, defects or problems can be identified earlier in the process, which helps prevent issues from moving further down the production line[25]. There are emerging methods, especially related to the rapid development and use of AI, in the future of quality control that are expected to play a key role in improving accuracy and efficiency. These technologies enable more reliable defect detection and support continuous quality improvement and these methods will be presented in the following sections.

2.7.4 Artificial intelligence

Artificial Intelligence (AI) serves as the overarching field concerned with developing systems capable of performing tasks that normally require human intelligence. In the car industry, AI is applied to detect problems, estimate failures and optimize processes.[25]. According to [9], traditional quality control at assembly stations relies heavily on human judgment, which results in slower response times and a predominantly reactive approach. Because operators must visually inspect components and decide whether a deviation is critical, the process becomes vulnerable to fatigue-related oversight and inconsistent decision-making. Building on these observations, recent developments in AI-based defect detection and deep-learning vision models enable real-time, automated identification of anomalies directly during assembly. These systems can detect subtle defects, predict emerging issues before they manifest physically, and identify patterns that humans typically overlook. As highlighted in [9], integrating predictive quality analytics with the help of using AI transforms quality control from a reactive checkpoint into a proactive, continuous assurance mechanism capable of preventing defects and foreseeing operator mistakes.

2.7.5 Computer vision systems

Computer vision systems for industrial object recognition have increasingly shifted toward 3D sensing, driven by the demand for more accurate and robust information in automated environments. Modern 3D optical sensors operate by projecting electromagnetic energy from an object and measuring the reflected or transmitted

signal to reconstruct object geometry. Within robotics, these sensing modalities are integrated to provide machines with better perception, enabling interaction with complex environments, object manipulation and coordination with other automated systems[21].

Modern vision systems can be deployed effectively when the image-acquisition setup is designed correctly. Fixed cameras offer a straightforward way to automate inspection and quality-control tasks, but they come with a major limitation: they are inflexible and therefore poorly suited for many industrial environments, especially when the goal is to monitor what is happening inside a vehicle. In such situations, the camera must capture images of components that may be hidden behind other parts or obstructed by the vehicle body. Fixed cameras can also interfere with the workspace and obstruct human operators or robots working at the station[21]. Computer vision is closely linked to AI and ML, as many advanced inspection systems rely on learning-based algorithms to interpret visual data.

2.7.6 Machine Learning

Machine Learning (ML) is a subset of AI that focuses on algorithms that learn patterns from data rather than relying on explicit programming. ML, as part of AI, is being used in quality improvement to enhance typical statistical quality control (SQC) processes[25]. Instead of relying only on traditional inspections, ML models trained on sensor data can be used to make quality forecasts and replace some of the usual inspection steps.

In the case of quality control, machine-learning-based approaches have enabled on-time part inspection, reducing the dependence on manual inspections and improving early defect detection in highly automated manufacturing lines[25]. By integrating these models directly into the production flow, inspections can be carried out continuously rather than at fixed checkpoints, which helps identify deviations sooner. This shift allows potential issues to be addressed earlier in the process.

2.7.7 Deep Learning

Deep Learning (DL) is a specialized branch of ML based on multi-layered neural networks capable of extracting complex features from images. DL has become a key technology in automated visual inspection due to its ability to detect subtle defects with high accuracy. AI tools such as DL have strengthened prediction and identification capabilities with high precision. These methods make it possible to detect problems earlier and with greater accuracy compared to traditional approaches[25]. AI tools such as DL provide better performance in image recognition, pattern recognition and sequence modeling, which makes them well-suited for identifying defects in assembly lines using sensor data. These capabilities allow systems to detect irregularities more reliably and consistently than traditional methods. As these models improve, they can support more autonomous manufacturing[30].

The article [30] indicates that DL can provide an increase in accuracy and time savings compared to manual inspection, showing that these AI-based methods can perform the same tasks more efficiently. It also highlights that there is a future potential to automate larger parts of quality-assurance procedures and to enable predictive maintenance in manufacturing environments. One of the main advantages that is mentioned is that DL in quality control contain the capability to detect minor or obscure defects which is particularly valuable, as these are often overlooked by human inspection or difficult to identify with the naked eye during manual checks.

Deep-learning-based systems do not require the underlying computer system to be manually adapted every time new products or tasks are introduced[24]. This could be beneficial for harness assembly stations, where the wiring harness differs between models and variants. Since assembly stations from time to time change configurations, a DL-based quality control system can adapt more quickly, retrain on new harness variants and avoid the need for manual re-engineering each time a new model enters production.

However, there are still a number of challenges that need to be addressed before these systems can be fully useful in a future, more automated factory and assembly workstation. This includes the need to handle large, high-quality datasets, which are required for training and maintaining reliable models. Another challenge is the integration of these tools with existing manufacturing systems, where compatibility and stability must be ensured. Finally, the adaptability of these solutions remains an issue, as they must function effectively in environments that change over time and involve varying products, tasks and conditions[30].

2.7.8 Object Detection

Object detection is a DL-based technique that identifies and localizes specific components or defects within an image. Object detection can be used to analyze images of the component of interest and determine whether a specific part is present or missing[24]. It is also effective for identifying whether configurations are normal or abnormal, which can be used to support quality control decisions. This capability makes it particularly suitable for the wire-harness station, where reliable identification of correct component presence, routing, orientation and variant selection is essential for ensuring assembly accuracy.

One study on using cobots with a camera for inspection tasks[21] concluded that the cobot could inspect parts as intended in the tasks it was designed to. In this case, the tasks had longer cycle times, allowing the cobot to operate at speeds suitable for collaboration with humans. This study confirmed that the operator could select which parts should be inspected by the cobot and the cobot was also adaptable enough for it. The study further indicated that improvements in cobot capabilities could increase the adaptability and scalability of the application to other processes. The cobot application had been in operation for six months and was reported to have achieved positive results.

3

Methods

The methodology combines qualitative data collection, literature analysis and simulation assessment to develop and evaluate a future concept for the harness assembly station.

3.1 Research design

A case study aims to analyze, in detail, the complexity and specific conditions of a single case. Such studies are typically conducted within one organization or at a specific location, such as a factory or office, or they may focus on a single event [6]. In this report, the case concerns the harness assembly station at Volvo Cars' final assembly. A case study strategy is appropriate because the research examines a single real-world workstation where context and the organizational conditions are central to understanding the current situation and the challenges associated with future workstation development.

3.2 Literature

Research in this field is developing rapidly, making a systematic literature review important for identifying recent advances and establishing the current state of knowledge [37]. A central purpose of a literature review is to understand the main ideas within the study area. The most important task is to identify what is already known so that the research does not “reinvent something that is already known” or repeat established findings. This involves understanding how other researchers have approached the topic, what theories are relevant to the project, whether there are controversies or conflicting perspectives and which questions remain unanswered. Modern electronic databases contain vast collections of academic journals, making it possible to evaluate the credibility of sources by considering factors such as the author's background, potential motives and when the material was last updated. Conducting this review ensures that the project is grounded in existing knowledge that can be applied to the case of this study[6].

A literature review was conducted to establish the theoretical foundation for the project. Scientific articles were identified using Google Scholar and the Chalmers Library database, which provided access to peer-reviewed literature. Search terms included combinations of keywords such as automation, assembly, Industry 4.0, Industry 5.0, manufacturing systems and harness. Boolean operators such as AND,

OR and NOT were used to refine the searches and identify relevant articles and papers.

The literature review focused on ergonomics in assembly work, automation trends, digitalization and the design of flexible workstations compatible with future manufacturing. Insights from the review were used to define design criteria and support the analysis of the current station.

3.3 Qualitative data collection

To understand the current state of the harness assembly station, qualitative data were collected through interviews with experts in the field of manufacturing and direct observations. Semi-structured interviews with engineers and experts from robotics and manufacturing engineering provided insights into the workstation and improvement opportunities. Informal discussions with operators were also used to capture practical experiences and recurring concerns, such as back strain and physical discomfort. These qualitative methods guided the identification of relevant areas for the development of the future workstation concept.

3.3.1 Observations

Observation is an effective research method because it allows the researcher to study work as it actually happens, rather than relying solely on descriptions or assumptions. By being present in the real environment, it is possible to capture details that occur in the area of observation [23]. This makes observation especially useful in production settings, where many tasks are performed by experienced workers.

The observations were conducted on-site at the wire harness workstation during a full production day, where the authors also participated in selected assembly tasks to gain a practical, hands-on understanding of the process. This combination of observation and participation made it possible to study operator movements, ergonomic challenges, task sequences and the interaction between humans, tools and equipment in a realistic context. Throughout the shift, continuous notes were taken focusing on bottlenecks, standard procedures and difficult tasks.

To complement the station-specific observations, several production walks (gemba walks) were carried out in other areas of the factory. These walks enabled the researchers to examine existing robotic and automated solutions used elsewhere in the plant, providing valuable reference points for evaluating which technologies could be realistically transferred to or adapted for the wire harness workstation. Together, the observations, hands-on experience and gemba walks formed a crucial empirical foundation for identifying current challenges and informing the development of feasible future workstation concepts.

3.3.2 Semi-structured interviews

There are multiple ways to gather information from people, ranging from structured interviews to open-ended group discussions. A method that blends these two is the semi-structured interview, which combines predetermined questions with the flexibility to explore new topics that can emerge during the conversation. Semi-structured interviews can include both open-ended and closed-ended questions as well as giving the interviewer the opportunity to ask follow-up question[1]. Oftentimes the interviewer has written a list of questions prior to the interview, but in a semi-structured interview the order of the questions can vary [6].

While semi-structured interviews offer flexibility and the ability to capture rich insights, they also come with several challenges. To avoid problems during the interview, it is important that the interviewee is knowledgeable about the topic, as the method relies heavily on their ability to provide detailed responses during the interview time. Semi- structured interviews are also time-consuming to conduct, since each session requires preparation, active facilitation and follow-up probing. In addition, the analysis phase can be lengthy, as the open-ended nature of the responses often results in large amounts of qualitative data that must be interpreted and analyzed[1].

The interviews were conducted by both authors using predefined discussion themes, while follow-up questions were asked when clarification or additional detail was required. The respondents were informed about the purpose of the interviews and consented to the interviews being recorded. The recordings were made using a mobile phone application that generated transcripts, which were used together with digitally written notes to support the subsequent analysis. Access to the recordings, transcripts and notes was limited to the two authors. During analysis and reporting, the respondents were anonymized and no names or other directly identifiable information was included in the thesis. The recordings, transcripts and identifiable research material were retained only for the duration of the thesis work and were deleted after completion of the study. The main discussion themes used to guide the semi-structured interviews are presented in Appendix 1.

Table 3.1: Overview of the conducted interviews, including the number of respondents, their roles and the duration of each interview.

Interview	Amount	Role	Time
Interview 1	1	Acting Manager, ME	2h
Interview 2	2	Technology Development, ME	2h
Interview 3	1	Technology Development and Robotics	1h

The semi-structured interviews presented in Table 3.1 were conducted exclusively with engineers and specialists from the relevant departments at Volvo Cars. This respondent group was selected because they possess detailed technical knowledge

of the wire harness process, current system limitations and the feasibility of future automation technologies. Their insights provided a deeper understanding of system-level challenges, integration requirements and long-term development trajectories that cannot be captured through operator-focused observations alone. By concentrating the interviews to people in engineering roles, the study ensured that the collected data aligned with the thesis aim of evaluating future technologies and defining a realistic next-generation workstation concept.

3.4 Simulation Assessment

The proposed future workstation concept was evaluated through digital simulation. A detailed digital model of the workstation was developed in Rockwell Emulate3D to analyze the behavior of the proposed station under representative operating conditions. The model included the moving conveyor and the integration of the proposed automation technologies.

The simulation model was used to evaluate whether the future workstation concept aligned with the requirements identified during the study, including takt time and automation feasibility. Because the selected case involves wire harness assembly early in the final assembly line, the station must support access to all relevant points in the cabin and accommodate the integration of promising technologies. As current simulation software cannot accurately model the physical behavior of deformable linear objects (see Section 2.3), the wire harness itself was not simulated. Instead, a rigid object matching the harness's approximate dimensions and weight was used as a proxy, allowing the layout, movement sequences, reachability and line-speed compatibility of the proposed station to be assessed. The simulation does not evaluate the physical manipulation, deformation or handling behavior of an actual wire harness

3.5 Data Analysis

The collected data from interviews, observations and gemba walks were analyzed carefully. All notes and interview summaries were first reviewed to identify recurring patterns related to operator challenges, ergonomic issues, technological limitations and opportunities for future automation. These patterns were then grouped into preliminary themes, which were refined to ensure consistency and alignment with the research questions. The observational data were used to support and contextualize the interview findings, particularly regarding workflow characteristics, bottlenecks and how human and technology could interact in the future. Insights from the gemba walks were analyzed separately to identify transferable automation solutions used elsewhere in the factory. The combined analysis formed the basis for the requirement formulation and guided the subsequent concept development. The qualitative data from interviews and observations was systematically collected and translated into operational, ergonomic and integration requirements, ensuring that the concept development is grounded in real needs identified at Volvo Cars.

The insights from interviews and observations were systematically translated into the final requirements through an iterative coding and consolidation process. First, all identified challenges, needs and improvement opportunities were grouped into preliminary categories based on thematic similarity. These categories were then compared to ensure that each requirement was supported by multiple empirical inputs. Finally, the themes were refined into clear operational, ergonomic and integration requirements that directly reflected the recurring patterns observed in the empirical material. This structured approach ensured that the final requirements were grounded in evidence and aligned with the practical realities of the workstation and the plant in general. This process ensured a direct and traceable link between the empirical findings and the final requirement set, making it clear how each requirement originated from the observed challenges and the insights gathered during the interviews.

The simulation work was used to assess selected operational aspects of the proposed workstation concept. The model was developed in Emulate3D based on findings from observations and interviews. It was used to examine workstation layout, AGV/-cobot movement sequences, approximate reach and compatibility with the moving line. Detailed cycle-time performance, travel time, waiting time and physical wire harness manipulation were not quantitatively evaluated. The simulation therefore provided preliminary visual support for the proposed concept rather than a detailed performance validation.

The insights gathered from interviews and observations are analyzed and translated into derived requirements, which are presented in Chapter 5. These requirements form the basis for evaluating different future workstation concepts. The technological possibilities identified in the literature review are then used to assess the feasibility of each concept in a structured and systematic manner. Finally, the selected concept is tested virtually in Emulate3D to illustrate its functionality and evaluate its potential performance in a future production environment. For example, observations showed that operators frequently performed bending, twisting, leaning and extended reaching during harness installation. These findings were grouped under the theme of ergonomic strain and limited reachability. This theme was then translated into the requirements “Reduced ergonomic load” and “Improved reachability,” which specify that awkward postures and excessive reaching should be minimized in the future workstation.

4

Case Study

The installation of wire harnesses into products is a highly complex task[26]. This challenge is present across many industries, including the vehicle manufacturing sector. There is an increasing electrification of automobile components, and the importance of wire harnesses continues to grow[11]. The wire harness is already one of the most expensive electrical individual components in vehicles as of today. Wire harnesses play a crucial role in modern vehicles. They ensure the effective distribution of power and data, as well as the integration of controllers and various non-electrical devices. New products require extensive connectivity, along with additional functions and sensors that depend on wire harnesses and the need for wire harnesses grows accordingly[26]. To investigate these dynamics in a realistic industrial environment, detailed empirical observations of a manual wire harness assembly line were conducted during a field study at the Volvo Cars Torslanda plant in Gothenburg, Sweden. The current assembly station layout, illustrated in Figure 4.1, is staffed by five operators, where Operators 1–3 perform their tasks in parallel during the first cycle, while Operators 4–5 engage in the second cycle once the initial trio has completed their work and advanced to the next vehicle.

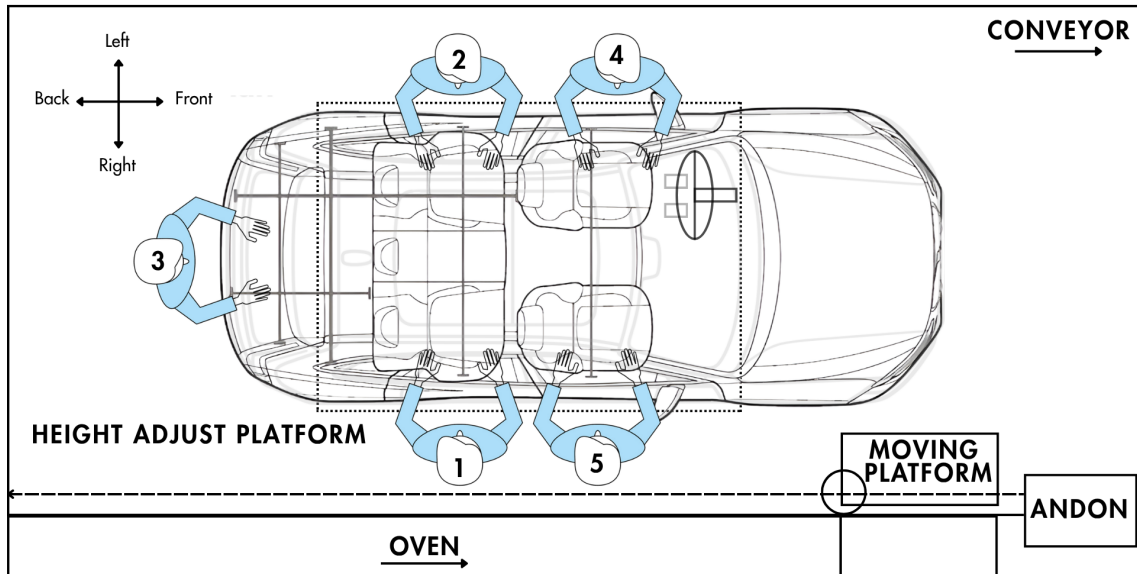


Figure 4.1: Current assembly station

4.1 Equipment at the Current Station

The studied assembly station operates as a continuous segment of the main vehicle assembly line at the Torslanda plant. The vehicle chassis are carried through the station on a moving conveyor belt system. Because the line operates under a strict continuous flow, the operators do not work on a stationary vehicle. Instead, they must dynamically walk alongside and move with the progressing car body to perform their routing and clipping tasks. Upon completing their respective portions of the 60-second work cycle, the operators immediately walk backward to the station's entry boundary to begin the sequence on the next incoming vehicle chassis

4.1.1 Wire Harness

Before the wire harness bundle arrives at the workstation, it is pre-fitted with a high density of specialized plastic fastening mechanisms, commonly referred to as fixation clips or attachment tags. These components serve as the primary structural interface that secures the flexible wire loom to the sheet metal vehicle chassis. As illustrated in Figure 4.2, these elements are engineered in various geometric designs depending on their specific mounting location and structural requirements within the cabin.

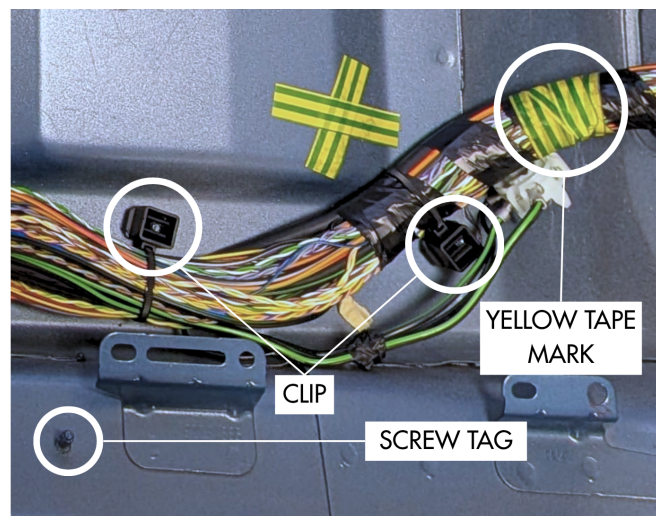


Figure 4.2: Pre-installed fixation elements

The fixation elements feature dual-sided functional designs. The upper portion typically consists of a retaining channel or integrated strap that clamps firmly around the wire bundle branches to hold the individual conductors together. The lower portion features mechanical locking geometries, such as arrow-head spruce clips, expansion anchors, or slide-in blocks, engineered to snap securely into pre-punched holes in the vehicle panels. During the assembly cycle, operators must manually align each clip with its matching chassis aperture and apply localized thumb pressure until the mechanism locks into place.

4.1.2 Thermal Conditioning Oven

The oven is primarily used to heat the wire harness bundles prior to manual installation onto the vehicle chassis. Heating the polymer insulation and underlying protective shielding increases the material flexibility of the bundle. This reduction in material stiffness makes it easier for human operators to bend, manipulate and route the harness within tight geometric spaces. However, because it must maintain constant elevated temperatures, this thermal conditioning system represents one of the most energy-consuming pieces of machinery at the assembly station.

4.1.3 Lifting Assist Device

This device functions as a gantry-mounted mechanical transport carriage suspended from an overhead rail network, serving as the physical link between the preheating oven and the vehicle chassis. While automated variants of this equipment exist in other European manufacturing plants that is incorporating hydraulic slide-in mechanisms where the operator merely presses a button to guide an automated stage inside the vehicle, the system implemented at the Torslanda factory is entirely manual.

4.1.4 Vehicle Height Adjustment System

Because the station accommodates five operators working simultaneously across different ergonomic zones, adjustable vertical clearance is critical. Operators One and Two, that will be described in the following section, require a highly stable vehicle position and maximum physical reach into the center of the cabin from behind the seats to calibrate the initial routing path. To facilitate this deep reach without causing excessive physical strain, the vehicle chassis is initially carried at a lower height.

Once the initial calibration and internal transfers are complete, operator Three, Four, and Five require different vertical clearance zones to fasten lower fixtures to the chassis. Consequently, the lift system automatically raises the vehicle chassis to a higher position during the second half of the cycle, optimizing ergonomic access and reducing cycle times for final assembly.

4.1.5 Andon System

In accordance with lean manufacturing principles, an Andon system is utilized at this station to signal operational disruptions and request immediate supervisor support. The system consists of a physical pull-cord routed along the upper framework of the workstation. When an operator encounters a quality defect, safety hazard, or cycle delay pulling the cord triggers visual and acoustic alerts on the area dashboard. This notifies the line supervisor to deploy immediately to resolve the issue, ensuring that standard line flow is maintained without halting the entire production line.

4.2 Operator Roles

The assembly station features five operators whose synchronized cycles span from the extraction of the thermal conditioning bundle from the oven to securing all placement tags into their respective slots for downstream processing. To systematically evaluate efficiency and ergonomics, the work tasks for each position were analyzed in detail during an approximately 60-second cycle using both Operator Instruction Sheets (OIS) and Work Element Sheets (WES). The OIS outlines the standardized sequence and timing of tasks an operator must execute during a work cycle. It classifies each process element as value-adding (VA), non-value-adding (NVA) or necessary but non-value-adding (NNVA), highlighting operational inefficiencies. Complementing this, the Work Element Sheet (WES) provides a breakdown of these tasks into smaller sub-steps, accompanied by visual aids and photographs. Combining these tools captured both the formal process design and the practical execution observed on the shop floor, including task order, cycle-time distribution and physical ergonomic demands.

4.2.1 Operator One

Operator One is responsible for removing the preheated wire harness from the thermal conditioning oven. Preheating the harness increases material flexibility which significantly eases positioning and attachment into the appropriate chassis slots. The operator takes the harness bundle from the oven and places it onto a gantry-supported moving platform. At this stage, the wire harnesses are wrapped in temporary protective covers and secured with rigid ribbon ties.

The operator manually cuts the ribbon ties using a special tool, aligns the platform with the vehicle's rear right door frame and pushes the wire harness inside the cabin space. This manual push was identified as one of the most physically demanding tasks at the workstation and is therefore a suitable candidate for initial automation to reduce operator exposure to high physical loads. Figure 4.3 can be used to visualize how the wire harness looks from above and clarify how the work at the station is done.

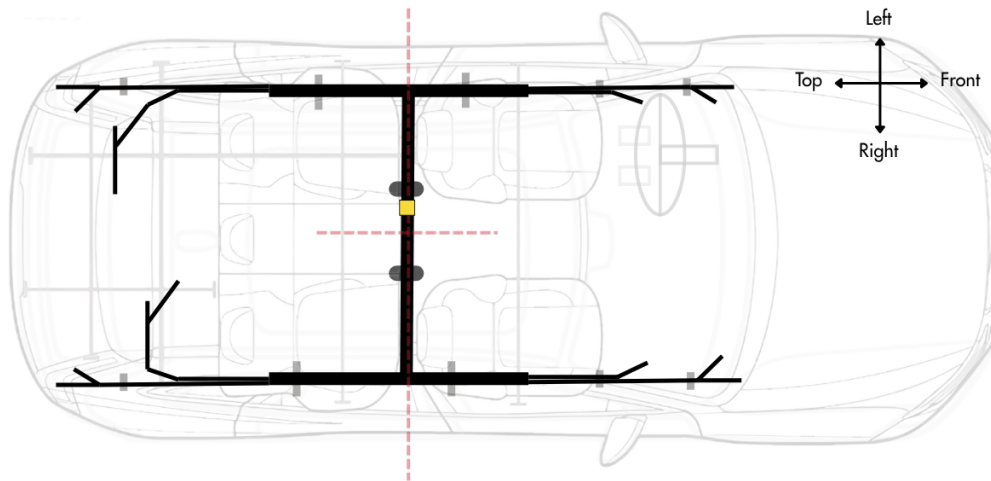


Figure 4.3: Schematic representation of the wire harness

The wire harness is structurally packaged into two main coiled and covered sections: a left section and a right section. After initial positioning, operator One passes the left section of the harness across the cabin to operator Two, and then uncovers the right section, separating it into front and rear sub-sections. The operator places the discarded packing cover on the front left seat area of the car body and begins attaching the structural clips.

To calibrate the alignment of the entire operation, the operator starts with a specific first clip which can be identified by yellow tape next to it. Next, the operator secures the clips located along the lower and middle portions of the rear right door frame. Finally, they assemble the clips behind the door, leaving the extended rear section loose for subsequent final assembly at the back of the vehicle by downstream operators.

4.2.2 Operator Two

Once operator One feeds the left portion of the wire harness across the cabin, operator Two executes a matching sequence of operations on the left side of the vehicle body. They uncover the left harness section, place the temporary cover in the front left seat area, and separate the front and rear subsections.

Operator Two then fastens the structural clips located at the bottom of the rear left door before moving toward the rear side of the car to perform secondary connections. The remaining rear layout tasks are left for the subsequent operator. Finally, operator Two gathers the accumulated packing covers from the front part of the car and disposes of them in a waste bin. Their primary objective is to ensure the left side of the harness is structurally secured for downstream operators.

4.2.3 Operator Three

Operator Three is positioned exclusively at the rear end of the vehicle body (as illustrated in the central cargo zone of Figure 4.1), handling all extended sections of the wire loom. The operator begins by routing the wire harness through the right side of the rear cargo compartment. This area features a higher task density and requires more intricate manual manipulations than the left side.

The operator must perform precise operations, including threading the flexible wiring bundle through various structural body panel apertures to establish the correct installation length, followed by locking the terminal ends of the harness into place. Conversely, the rear-left architecture requires fewer manual adjustments, consisting primarily of anchoring standardized clips in a predefined chronological sequence. Ultimately, Operator Three's role is to finalize all structural fixtures and harness terminations at the rear end of the vehicle chassis.

4.2.4 Operator Four

Operator Four is responsible for the final routing and clipping of the forward-right section of the wire harness (located toward the front right zone in Figure 4.1). While their standard clip-attachment tasks mirror the manual clipping methods utilized by Operators One and Two, this role involves a distinct technical responsibility: connecting the wire harness directly to the integrated seat belt sensors. This task represents the only operation at this workstation that involves a direct electromechanical connection to an active sensor subsystem, adding a layer of component sensitivity regarding pin alignment and connector mating force.

4.2.5 Operator Five

The final worker, operator Five, has a work cycle that is less focused on the physical routing of the main wiring bundle. Positioned at the front-left zone of the line (see Figure 4.1), they finalize the remaining harness clips on the forward-left side of the vehicle body.

Their primary responsibilities then transition to mechanical assembly and quality control. The operator utilizes an industrial power tool to tighten structural chassis screws to a specified torque and scans the barcodes on the seat belt sensors using a handheld reader. This scanning step logs the component traceability data directly into the factory's manufacturing execution system (MES), completing the operational cycle for the wire harness assembly station.

4.3 Current State of Wire Harness Automation

At a general level, most tasks involved in assembling wire harnesses onto vehicle bodies are carried out manually[26]. This is certainly true for the studied harness assembly at the Volvo Cars factory in Torslanda. In this station, a lifting device is

available to support the operator by reducing the physical effort required to move the heated harness bundle from the oven and position it inside the car body. However, the operator still needs to drag or pull the lift with the wire harness positioned on it. The most unergonomic moment arises when the operator has to exert substantial physical force to push the relatively heavy bundle off the lifting device and into the car body. Apart from that, there is very little assistance available for the operator. No tools or aids are provided to help with gripping or lifting the cables, and there are no devices that assist with attaching the clips. All of these tasks must still be performed manually at this stage, as observed during the visit to the station.

The working conditions are not ideal for the operators, since several of the tasks involved in wire-harness assembly result in unergonomic postures and can negatively affect worker health[26].

4.4 Current Challenges in Wire Harness Assembly Automation

Although interest in DLOs has been growing recently, several challenges remain when manipulating them with the use of robots. One of the most critical issues in the specific case of wiring-harness manipulation is the gripping procedure. For DLOs, there are primarily two aspects that are essential: how to grip and where to grip. In this context, grasping refers to establishing a stable contact that allows the robot to control the object without causing unwanted deformation of the cables. This is significantly more difficult than grasping rigid objects due to the DLO's shape variability and its tendency to deform during contact[7].

Current object-detection methods are still not fast enough for many industrial needs, and vision-based automation has yet to reach the robustness of human performance, particularly when dealing with dynamic production environments. As a result, these systems often struggle to maintain reliability under changing configurations that human operators can handle[42].

To achieve successful manipulation, predefined grasp points and stable contact conditions are often used. Many research experiments on DLOs are conducted in simplified environments typically planar setups without obstacles or complex interactions and often focus on basic pick-and-place tasks[7]. Gripper positioning for deformable objects therefore centers on identifying optimal grasp locations that minimize deformation while maximizing control which is greatly important to achieve reliable results.

Routing, in turn, involves arranging the DLO to match a target configuration while simultaneously fastening it to environmental features such as clips, jigs, or pivot points. This requires the robot to manipulate the DLO into place while accounting for contact interactions, bending behavior and the constraints imposed by the surrounding environment[7].

Looking forward, reliable DLO manipulation increasingly requires force and tactile feedback to work correctly. Although DLO manipulation is a highly active and rapidly advancing research area, it has not yet reached the level of maturity needed for widespread industrial deployment. Even in controlled environments, a DLO can create complex and cluttered conditions on its own, including self-occlusions, knots, and tangles[7]. As a result, robustness against these intrinsic dynamics is essential for any practical manipulation system.

5

Results

This chapter presents the empirical findings and analyses conducted in the study. The results include identified needs, derived requirements and an assessment of the future technologies that were presented in section 2.4 that could be relevant for designing the future harness assembly station. The results presented in this chapter follow a structured flow, beginning with empirical findings, translating these into requirements and using those requirements to guide the concept development and selection process as well as finally evaluating it with the use of a simulation model.

5.1 Empirical Findings and Identified Needs

The empirical findings presented in this section form the foundation for the derived requirements in Section 5.3. These requirements are directly based on the challenges, needs and constraints identified through interviews and observations.

5.1.1 Interview Findings

According to the interviewees, the key performance indicators (KPIs) ultimately determine the direction of the station design. Sometimes, the priority is to keep the solution as inexpensive as possible in order to save money, while in other cases a higher level of automation is required. The reason for changing and improving the workstations can also be due to the worker's well being and health and in those situations focusing on the ergonomic aspects are important. This depends entirely on the situation and the goals set for the station.

One of the interviewees emphasized that it is important for the work to be easy to standardized, and that ergonomics often is a very important factor in the decision making process. The station must deliver the right quality and because every step in the process takes time, minimizing the number of steps is essential. Reducing unnecessary movements saves time and contributes directly to efficiency. The respondent also stated that the target is to achieve 65 percent value-adding time, which guides how the station should be structured and optimized.

Cycle-time feasibility is an requirement the most critical constraint. If a task cannot be completed within 50–60 seconds, it must be split or redesigned. As it is today, the harness assembly consists of two separate stations as the aforementioned operator roles assigned to two different cycles where operator 1-3 are working with the first

part of the harness assembly and operator 4 and 5 start working for 60 seconds after the first 3 operators are done. The conveyor belt moves around six meters every 60 seconds and that is where the operation needs to be finished.

All of the interviewees highlighted that the moving assembly line introduces significant complexity for both current operations and future automation. Because the car body continuously moves through the station, any automated solution must function correctly as the line speed will not be adjusted. This increases technical difficulty and reduces the tolerance for delays or repositioning. The interviewees emphasized that the current assembly line operates as a continuous-flow system, where the car body moves steadily through the production area without stopping at each station. They explained that the plant deliberately avoids stop-and-go stations. A stop-and-go setup where the car body moves to a station, stops while tasks are performed, and then moves to the next would require additional buffers between stations which in turn would increase system complexity and disrupt the overall flow.

New solutions must ideally pay back within 12 months and must have a positive business case. Although one of the respondents mentioned that the return on investment period can be prolonged if the new solution can significantly improve the ergonomic situation at the station and minimize the physical risks for the humans.

The respondents told that high product variation needs to be handled and makes automation difficult since the cars are different to each other already at the wire harness assembly station. To design a workstation in a future scenario, it will be greatly important that future tools and automation solutions also are compatible with future platforms and models.

The environment must ensure safety for humans especially on a moving assembly line. The amount of humans on the factory floor might be reduced in the future but there will still be a need to let people be at the station in the future. More people will work in a supervisor role for the new technologies or carry out corrective operation if the potential robot implementation suddenly fail.

The interviewees emphasized the importance of minimizing manual lifting and ergonomically demanding tasks in future station designs. They noted that several current activities involve awkward postures, force-intensive movements, or repetitive handling of heavy or unstable components. According to the interviewees, reducing these physical loads is essential for operators.

Several interviewees stressed that future solutions should be standardized and scalable across multiple plants globally. They explained that developing unique, plant-specific solutions increases complexity, cost and maintenance effort. A standardized approach, on the other hand, enables the best practices, easier training and more efficient implementation of new technologies. Ensuring that the station concept can be replicated or adapted across different manufacturing sites was therefore identified as an important strategic requirement.

A future station must allow manual fallback if the automation technologies does not work as intended. Humans need to be ready and have knowledge of the station and the tasks in order to take over so that the line does not stop for a long period of time because that will interrupt the entire system and be extremely costly. It is also important that the workstation can allow humans in case of a mistake so that an operator can quickly adjust the mistake so that the robots can start working again.

Ability to test technology before it will be rolled out to the plant so that the risk factor will not be too high as mistakes and disruptions has a high cost. It was also mentioned that if implementing something that does not work, the plant will likely not trust the designers of the station anymore.

The specific wire harness assembly station must handle dynamic positions. This includes to be both capable of carrying out the operations while the car is moving and also to handle the deformable wires. Most likely if automation will be implemented it will require a vision system to detect part orientation and positions.

Ease of integration into the factory will be important as minimizing the need for rebuilding infrastructure or adjusting digital connections will be time consuming and costly. The solution for the future station should preferably affect the other operations on the line as little as possible.

5.1.2 Observational Findings

The observations revealed several ergonomic challenges in the current harness-assembly process. Operators frequently performed bending, twisting and leaning movements and many tasks required fine-motor work with the fingers when manipulating clips and connectors. Several assembly points were located outside the operator's natural reach zone, forcing them to extend their arms outward or reach deep into the car body.

It was also noted that operators often needed to reposition the harness multiple times during the assembly sequence. The flexible nature of the cable bundle made it difficult to control and operators frequently used both hands to stabilize or guide the harness into the correct position. These small adjustments contributed to variation in task execution and added small delays to the workflow.

Identifying which clip belongs to which attachment point was not always intuitive, leading to short pauses and increased cognitive load. The high number of clips that looked similar and the lack of clear visual cues made this step more demanding.

Finally, the observations indicate that any future automation solution would face similar reachability and manipulation challenges. A robotic system would need access to all connection points inside the car body and would need to handle the same

flexible, deformable harness that currently requires two-handed control and repeated repositioning.

5.2 Interview Findings on Future Technologies

Vision-guiding was mentioned by all interviewees as promising for the future in final assembly. They expressed that they are investigating vision guiding on moving line. It is also a promising new technology that is possible to implement in bin picking applications as an assistant to the human. It was also revealed that vision-guided bolting is being tested now and is also promising in terms of hole detection. Vision guiding technology has also been used and tested for tasks such as emblem placement, adhesive application and handling components.

Other new technologies that were mentioned by all the respondents was cobots. As of now cobots are used in isolated cases at Volvo Cars but not widely adopted in the final assembly environment. If it were to be implemented in an assembly station it would be crucial that the cobots on the station would be cost-competitive as it will only be implemented if it can save money. If it can save a salary it might actually be cheaper to install a cobot than using a human. It also must be integrate with vision systems.

According to the interviews it is expected that in the upcoming 5-10 years that the operators will do less repetitive, low-skill work. They will likely focus More on supervision, problem-solving, handling exceptions in the final assembly. Automation will primarily take over tasks that are ergonomically harmful or hard to staff. Operators will supervise and collaborate with cobots rather than perform all manual tasks. Operators will likely handle exceptions and flexible tasks. Final assembly remains one of the least mature areas in terms of automation and a balanced approach is also needed during the transition period to more automation.

One respondent mentioned driverless logistics as a promising future development. In their view, it represents a shift toward more automated material movement, where transport tasks could be handled by autonomous systems rather than manual processes. The respondent described it generally as a potential way to make internal logistics more efficient in the long term.

Designing the product and station together to enable a much smoother automation integration is probably also needed. Attempting to increase automation without ensuring that the product is actually designed for it is a common mistake.

5.2.1 What is preventing these technologies from practical implementation

Underestimating the installation cost of automation is a common mistake and the costs can be higher than expected. Integration complexity is a big obstacle when trying to automate assembly tasks, especially synchronizing robots with a moving line. Cycle time is the main barrier and many robotic tasks exceed the maximum allowed takt time.

Product design limitations some automation requires redesigning components, which is extremely expensive once a car is already in production. Existing stations are not designed for cobots, so integration requires rebuilding.

Stop-and-go systems require large buffers and disrupt line flow, making them unsuitable for Volvo's moving line concept. This would ease the integration of more technology but it is not feasible in the assembly system as it will disrupt and affect other stations and will therefore not be used.

5.3 Derived Requirements

The following requirements were developed by systematically translating the empirical findings into operational, ergonomic and integration requirements. Each requirement is directly linked to the challenges and opportunities identified in Sections 5.1 and 5.2. Both interview data and observations from the plant, were analyzed to identify recurring needs, constraints and challenges in the current harness assembly process. The derivation process involved comparing patterns from the interviews and observations and translating them into concrete requirements that reflect what the future station must achieve. These patterns were then interpreted and grouped into broader categories to create an overview that can support the later development of the concept. Together, these requirements form the foundation for evaluating future technologies and guiding the design of the proposed concept direction. The derived requirements are presented in separate tables, with each table corresponding to one of the three requirement groups.

5.3.1 Operational Requirements

This category includes the operational and flow-related requirements that emerged from the interviews and observations. These requirements define the fundamental constraints for takt time, line structure, efficiency and global scalability. Together, these requirements form the basis for how the future workstation must be organized. The source or evidence supporting each requirement is indicated in the tables using the abbreviations I = interviews, O = observations and L = literature.

Table 5.1: Operational & Flow Requirements

Requirement	Description	Source
Cycle-time	All tasks must be executable within the 50–60 seconds since the takt-time is 60 seconds. Tasks exceeding this limit must be redesigned or split into additional operations.	I
Continuous-flow compatibility	The workstation must support the continuous moving line and must not introduce stop-and-go stations as these require buffers and disrupt flow.	I+O
Scalable design	The solution should preferably be scalable across global plants to reduce complexity, support shared best practices.	I

5.3.2 Ergonomic Requirements

The ergonomic and human-centric requirements focus on reducing physical strain, improving operator safety and ensuring sustainable working conditions. These requirements reflect both observed ergonomic challenges and the interviewees' emphasis on minimizing manual load and supporting safe human–automation interaction.

Table 5.2: Ergonomic & Human-Centric Requirements

Requirement	Description	Source
Reduced ergonomic load	Manual lifting, force-intensive tasks and awkward postures must be minimized to reduce physical strain and long-term ergonomic risk.	I+O+L
Improved reachability	All assembly points must be accessible without excessive bending, twisting, leaning, or extended reaching outside the natural work zone.	O+L
Support for deformable components	The workstation must support stable handling of flexible wire harnesses that require frequent repositioning.	O+L
Safe human–automation interaction	The environment must ensure operator safety on a moving line and allow safe coexistence with future automation solutions.	I+L
Manual fallback capability	Operators must be able to quickly take over tasks if automation fails to avoid costly line stops and maintain system continuity.	I

5.3.3 Integration Requirements

The technical and integration requirements describe the capabilities needed for future automation and implementation without risks. These requirements address synchronization with the moving line and the need for solutions that integrate smoothly

into the existing factory environment without affecting the surroundings too much.

Table 5.3: Technical & Integration Requirements

Requirement	Description	Source
Automation alignment	Any automated solution must synchronize precisely with the moving line speed, with minimal tolerance for delays or repositioning.	I+O
Compatibility with product variation	The workstation must handle high variation in car models and harness configurations and remain compatible with future platforms.	I+L
Vision-system readiness	Automation must be able to detect dynamic positions and orientations of deformable wires, likely requiring advanced vision systems.	I+L
Ease of integration	The solution must integrate into the existing factory with minimal infrastructure changes and minimal impact on surrounding operations.	I+O
Pilot testing and implementation risk	New technologies should be tested in a controlled pilot environment before production implementation. Testing should assess cycle-time compatibility, safe operation, integration with the moving line and reliable task execution. Further development should be supported if the technology can meet these requirements without disrupting production flow.	I

5.4 Concept Development

The concept development process is guided by the derived requirements established in Section 5.3. These requirements serve as evaluation criteria for assessing the feasibility and suitability of different future workstation concepts.

5.4.1 Concept Alternatives

The development of concept alternatives was guided by the derived requirements presented in the previous section, together with the technological insights from the Theory chapter and the practical constraints identified in the case study of the wire-harness workstation. By combining these perspectives, several potential workstation concepts were generated to address the operational, ergonomic and integration needs of the future station. Each concept represents a different approach to meeting these requirements and reflects varying levels of automation maturity, human involvement and technological feasibility. By presenting and analyzing each concept separately, the study ensures a systematic comparison that ultimately supports the selection of the most suitable solution for the next 5–10 years. The following subsections present and describe these concept alternatives, forming the basis

for the subsequent comparison and final concept selection.

5.4.1.1 Humanoid Robots and Quadrupedal Systems

The first concept explored the deployment of humanoid robots to execute the wire harness installation. Given their human-like kinematics, humanoids possess the theoretical capability to navigate within a vehicle chassis and manipulate flexible components effectively. While recent advancements indicate that humanoid robotics are increasingly capable of performing complex manual operations historically reserved for humans, current iterations still present significant operational limitations.

The primary constraints rendering humanoid robots unsuitable for this next-generation workstation are their limited mobility and slower execution speeds. In practical production environments, robotized wire harness installation remains exceptionally difficult due to the modeling and path-planning complexities of handling DLOs within a highly restricted takt time. Additionally, maintaining dynamic equilibrium and tactile precision when routing a flexible, heavy wire harness through tight interior spaces remains a substantial engineering bottleneck. While quadrupedal systems (robot dogs) offer high mechanical stability across industrial floors, they lack the high-degree-of-freedom upper-limb manipulators required to complete intricate secondary connections and clip fastenings within the targeted cycle time.

While humanoid robots theoretically address several ergonomic requirements by reducing physical strain, their current technological maturity, high integration complexity and limited reliability in handling deformable linear objects make them unsuitable for the specific conditions of the wire-harness workstation. As highlighted in the theory chapter and confirmed through the case study, the unpredictable geometry of the harness and the tight vehicle environment exceed the present capabilities of humanoid systems, placing this concept outside the feasible 5–10-year horizon. Also the legs of humanoids make it harder for them to operate on a moving assembly line.

5.4.1.2 Advanced Human-Assisted Workstation

The second concept focuses on retaining human operators on the assembly line while optimizing their performance through advanced technological assistance. In this configuration, operators are supported by real-time self-correction feedback and AI-augmented smart glasses to streamline cognitive workflows and mistake-proof (poka-yoke) the installation process.

Implementing advanced computer vision and collaborative assistance technology can serve as a vital tool to reduce cognitive load and guide operators along complex assembly trajectories. However, while this advanced human-assisted workstation appears technically achievable with state-of-the-art industrial technology, it fails to fully resolve the core physical challenges of the station. In automotive final assembly, wire harness tasks are traditionally manual and physically demanding, frequently resulting in severe ergonomic risks and occupational musculoskeletal issues due to

highly repetitive tasks and awkward body postures . Because the force-intensive clip insertions and overhead reaching would still be performed manually, this alternative does not sufficiently satisfy the long-term ergonomic health and safety objectives established for the future factory floor.

Although this concept aligns well with several operational and integration requirements, particularly those related to cognitive support and process transparency, it does not sufficiently address the ergonomic and physical demands identified in the case study. As emphasized in the Theory chapter, advanced assistance technologies can enhance decision-making and reduce cognitive load, but they cannot compensate for the force-intensive, repetitive and posture-dependent characteristics of wire-harness installation. Consequently, despite its technological feasibility and strong alignment with current industrial capabilities, this concept does not fully satisfy the long-term ergonomic and automation-readiness requirements established for the future workstation.

5.4.1.3 Industrial Robot System

The third concept explores a fully automated alternative utilizing stationary or rail-mounted heavy industrial articulated robots. In this configuration, high-payload robotic manipulators are responsible for retrieving the heavy, bundled wire harness, uncoiling it and physically maneuvering it into the vehicle body structure. Industrial robots offer unmatched repeatability, structural rigidity and the high force capacity required to firmly seat mounting clips and secure structural fasteners into the chassis.

However, handling non-rigid, flexible components like wire harnesses presents significant automation and financial hurdles. Resolving these errors requires a complex architecture integrating real-time 3D machine vision with precise mechanical force feedback or impedance control systems.

More importantly, serious operational and economic bottlenecks emerge regarding cycle management. If a tracking or insertion error occurs, stopping a high-speed assembly cycle and restarting the process to resume manufacturing introduces substantial down-time costs, making error recovery exceptionally expensive. Furthermore, because these industrial manipulators operate at very high speeds, safety regulations mandate a fully caged unit. Implementing a bulky, physically enclosed cage on a final assembly station where operations are largely continuous and non-discrete introduces major layout constraints and limits structural accessibility. This rigid containment drastically decreases overall line efficiency and leaves the station highly inflexible to rapid variations in vehicle customization. As emphasized in the Theory chapter, industrial robots excel in structured, rigid and highly repeatable environments, but their applicability decreases sharply when handling deformable linear objects that require continuous adaptation and real-time perception. Consequently, due to the possibly severe economic risks of cycle interruptions, the layout inefficiencies of safety caging and lack of operational flexibility this operation was deemed not applicable for the targeted scenario.

5.4.2 Exoskeletons

Exoskeletons represent a semi-automated ergonomic support solution designed to reduce physical strain during manual assembly tasks. They are typically worn by operators as either passive or active systems, providing support for the upper body, shoulders or lower back depending on the design. Within wire harness assembly, exoskeletons could potentially reduce muscular load during repetitive routing, reaching and clipping tasks, particularly in overhead or awkward postures.

The main advantage of exoskeletons is that they can be implemented without major changes to the workstation layout or process flow. They require minimal integration effort and have been tested in various automotive applications. However, their impact is limited to ergonomic relief and does not contribute to increased automation, reduced cycle time, or improved process consistency. Exoskeletons also introduce challenges related to operator comfort, long-term wearability, hygiene and acceptance, as not all operators tolerate wearing supportive devices for extended periods. Furthermore, exoskeletons do not address quality assurance.

Overall, exoskeletons offer a low-complexity, ergonomics-focused improvement but lack the technological capabilities required to support future automation goals. While they can reduce physical strain, they do not meaningfully enhance productivity or prepare the workstation for higher levels of automation, making them a less suitable long-term solution compared to more integrated concepts such as cobot-AGV collaboration.

5.4.3 Comparison of Concept Alternatives

The concept alternatives are compared against the derived requirements to determine which solution best satisfies the operational, ergonomic and integration needs of the future workstation. By contrasting the strengths and limitations of each concept, the analysis provides a clear foundation for selecting the most feasible and future-ready solution for the next 5–10 years. The comparison of the different alternatives is shown in Table 5.4.

Each concept was rated against the five criteria using a three-to-four-point qualitative scale (Low, Medium, High, Very High), based on the requirements derived in Section 5.3 and the findings from the literature review and case-study analysis presented in Chapters 2 and 4. Ratings were assigned through comparative judgment by the authors: a concept received 'High' on a criterion where the literature and case-study evidence indicated strong, well-documented performance with few significant limitations (e.g., proven technical maturity in comparable industrial applications), 'Medium' where performance was plausible but depended on conditions not yet confirmed for this application (e.g., partial evidence, or feasibility contingent on further development) and 'Low' where the evidence indicated substantial limitations or unresolved barriers (e.g., lack of technical maturity within the 5–10-year horizon, or high implementation complexity). This is a qualitative, comparative assessment rather than a quantitative scoring model, and is intended to support not

replace expert judgment in concept selection.

The qualitative ratings in Table 5.4 were assigned based on the findings from the literature review, interviews, observations and the derived workstation requirements. A Low rating indicates that the concept provides limited support for the criterion or presents substantial unresolved limitations. A Medium rating indicates partial support, where the concept provides relevant benefits but also has notable limitations or uncertainties. A High rating indicates strong alignment with the criterion based on the evidence considered in this study. For integration complexity, the scale is interpreted inversely: Low indicates relatively limited integration effort, while High indicates substantial changes to the workstation, infrastructure, or production process. The ratings are qualitative assessments used to compare the concepts and should not be interpreted as quantitatively validated scores.

Table 5.4: Comparison of concept alternatives against the defined evaluation criteria

Concept	Ergonomic Benefit	Safety	Technical Maturity (5–10 yrs)	Integration Complexity	Overall Feasibility
Humanoid Robots	High potential, but unproven in harness tasks	Medium	Low	High	Low
Industrial Robots	High for force-intensive tasks, low flexibility	High (with fencing)	High	Medium	Medium
Human-Assisted Workstation	Medium (tool- and feedback-dependent)	High	Very High	Low	Medium
Exoskeletons	Medium (reduces physical strain)	High	High	Low	Low–Medium
Cobots + AGVs (Proposed)	High (automates selected tasks, supports operators)	High (application-dependent)	High	Medium	High

As shown in Table 5.4, the evaluated concept alternatives differ significantly in terms of ergonomic benefit, safety, technical maturity, integration complexity and overall feasibility. Humanoid robots offer high theoretical ergonomic potential but lack the technical maturity required within the 5–10-year horizon. Industrial robots provide strong precision and force capacity, yet their need for safety fencing and extensive layout redesign results in very high integration complexity. The human-assisted

workstation and exoskeleton concepts improve cognitive support and reduce physical strain but do not address the core manual challenges of cable manipulation, force-intensive clip insertions and variant-dependent assembly.

In contrast, the cobot-AGV concept combines strong ergonomic benefits, a favorable safety profile relative to industrial robots and proven technical maturity with a moderate integration effort, although actual safety performance would depend on the complete application and a formal risk assessment. It is the only concept that simultaneously has the potential to reduce selected hazardous manual tasks, supports continuous flow and enables future automation through robot-friendly cable design. This makes it the most promising solution among the alternatives evaluated for the next-generation wire harness workstation. The comparison matrix ensures that the selection of the final concept is transparent, evidence-based and directly linked to the requirements derived from the empirical findings.

5.4.4 Selected Concept

Based on the comparison in Section 5.4.3, the cobot-AGV concept demonstrates the strongest alignment with the derived requirements and is therefore selected as the recommended solution for the next 5–10 years.

5.4.4.1 Cobots and AGVs

The selected concept integrates collaborative robots mounted on automated guided vehicles to create a mobile, flexible and human-centric workstation. AGVs are preferred over AMRs because the workstation does not require autonomous navigation or dynamic rerouting. Each unit only needs to follow the vehicle forward and return along a fixed path which makes AGVs simpler, more reliable for this application. Cobots include safety functions that can support collaborative operation with humans. Compared with conventional industrial-robot applications, this may enable closer human-robot interaction; however, the required safeguarding depends on the complete application and must be determined through a formal risk assessment. By mounting cobots on AGVs, the system gains mobility and can follow the moving assembly line, ensuring that each cycle begins at the correct position without requiring major changes to the existing conveyor infrastructure. This mobility mirrors the current human workflow, where operators walk alongside the vehicle during wire-harness installation.

A key motivation for selecting this concept is the ergonomic profile of the current workstation. The empirical findings showed that wire-harness installation involves several dangerous sub-tasks, including leaning into the vehicle, lifting and routing heavy or stiff harnesses, repetitive clipping motions and force-intensive insertions that expose operators to finger injuries. These risks were directly transformed into the derived ergonomic requirements, which emphasize reducing physical load, minimizing awkward postures and hazardous manual operations. The cobot-AGV concept has the potential to address these requirements by transferring selected physically demanding and repetitive tasks from the operators to the cobots, thereby potentially reducing exposure to some of the ergonomic challenges identified in the

current workstation.

Importantly, the concept does not aim to replace human operators. Instead, it aligns with Industry 5.0 principles by redefining the human role toward supervision, decision-making and in this case exception handling. Humans could intervene when the cobot encounters unexpected situations, supporting recovery and manual fallback when required. This preserves human expertise for critical tasks while removing them from ergonomically harmful work. In the long term, this human-centric approach has the potential to support operator well-being by reducing exposure to selected physically demanding tasks.

Human operators therefore remain an active part of the proposed workstation even as the level of automation increases. Trained operators would supervise the cobot–AGV system and intervene when the automated process cannot complete a task as intended. This includes handling unexpected harness configurations, correcting misplaced or incorrectly routed components, recovering the system after robot or vision-system failures and completing tasks manually when necessary. Operators must therefore retain sufficient knowledge of the assembly process to take over individual operations or, if required, temporarily perform the remaining assembly manually. This manual fallback capability is intended to prevent extended line stoppages and maintain production continuity while the cause of the automation failure is corrected. As the technology matures, the amount of direct manual work may decrease, but supervision and fallback remain important human responsibilities within the proposed workstation.

To enable increased automation of wire-harness installation, the concept includes redesigning the harness and associated clips to be more robot-friendly. The empirical analysis showed that deformable linear objects, such as cables, are difficult for robots to manipulate due to unpredictable geometry and variability. Current vision systems struggle to reliably detect, track and predict cable shape in real time, which limits the feasibility of autonomous cable handling. But the scope of the thesis is a time horizon of 5-10 years into the future. Therefore, the concept incorporates future improvements in vision-guided, where advanced 3D sensing, AI-based shape prediction and real-time tracking will support the cobot in grasping, routing and positioning the harness with higher accuracy as these advancements are likely to happen. By combining robot-friendly cable design with improved vision capabilities, the cobot–AGV system can gradually transition from partial automation to full automation as technology matures.

Overall, the cobot–AGV concept aligns well with the operational, ergonomic and integration requirements derived from the empirical findings. It has the potential to reduce operator exposure to selected physically demanding and hazardous manual tasks, support continuous flow through synchronized AGV movement, enable future automation through robot-friendly cable redesign and improved vision systems and preserve human involvement through supervision, intervention and manual fallback. This makes it a promising conceptual solution for the next-generation wire harness

workstation within the 5–10-year horizon considered in this study.

5.4.4.2 Vision-based inspection

To ensure consistent and correct installation, the selected concept incorporates an automated quality control system based on advanced vision sensors and deep learning. Instead of using drones that introduce unnecessary safety risks in confined vehicle environments and provide no functional advantage, the concept relies on fixed or cobot-mounted cameras that capture high-resolution images of the assembly during each cycle. Modern deep learning models, particularly object detection, could potentially be used to identify whether clips are fully seated, whether the harness follows the correct routing path and whether all required components are present. However, these functions would require development, training and validation using representative production data before implementation. By shifting quality verification toward an automated vision system, the workstation could provide a more objective and repeatable inspection step.

As vision technology continues to advance, these systems will not only detect errors but also support the cobot in manipulating flexible cables. Predictive vision models can estimate cable shape, deformation and future movement, enabling the cobot to adjust its grasping and routing strategy in real time.

Integrated directly into the cobot–AGV workstation, the quality control system performs inspection at the station, immediately after the cobot completes its task. This approach is superior to end-of-line inspection because it allows human operators to intervene instantly if the cobot encounters an unexpected situation or produces an incorrect installation. Immediate feedback could reduce the need for manual visual checks later in the process and, if successfully developed and validated, could provide automated verification of the installation before the vehicle leaves the station.

5.4.5 Selected Concept Description

The complete conceptual workstation consists of five cobot–AGV units, corresponding to the five operator roles identified in the current workstation. However, the five cobot configuration represents the longer-term configuration of the concept rather than the recommended starting point for implementation. The proposed transition should instead be gradual, beginning with the automation of one physically demanding and technically suitable operation. As the technology is physically tested and demonstrated to operate reliably and safely, additional cobot–AGV units could gradually be introduced. For Operator One, a heavy-load AGV is used because the corresponding cobot is responsible for placing the wire harness as a single load into the center of the car, in the rear-seat area. Although this position was originally intended for the rear-left seat, the cobot instead unfolds the wire harness for the entire right side of the car. Cobot Two then begins unfolding the wire harness once Cobot One has placed it inside the car on the right side of the chassis. Both cobots complete the initial placement of the wire harness before proceeding to the next

connection point.

Cobot Three automates the tasks currently performed by Operator Three and carries out wire harness connections at the rear of the vehicle. This includes routing the harness into the trunk area, securing the connectors and completing the rear-end attachment sequence. Cobots Four and Five automate the tasks currently performed by Operators Four and Five and work simultaneously with Cobots One and Two on the main wire harness installation along the sides of the vehicle. This represents an important improvement compared to the current case study, where Operators Four and Five begin their tasks only after Operators One and Two have finished and moved to the next vehicle. In the proposed concept, all side-mounted cobots are designed to operate in parallel throughout the entire installation cycle, which is intended to reduce idle time compared to the current sequential process. The simulation modeled the timing and motion paths of this parallel operation using a rigid proxy object; it did not model the actual insertion, routing, or clipping of the wire harness.

Each cobot-AGV unit moves alongside the vehicle at conveyor speed, maintaining its position relative to the car body just as human operators do today. The AGVs keep the cobots aligned with the intended installation zones while the modeled cobot motions represent the sequence and spatial positioning associated with the intended manipulation, routing and clipping tasks. The physical execution of these wire harness operations was not simulated. This parallel and synchronized operation supports continuous flow without requiring major changes to the existing conveyor infrastructure.

5.5 Future Cable Design for Automation

To successfully transition to a fully automated final assembly cell operating without human assistance, optimizing the robotic equipment alone is insufficient. The fundamental bottleneck in automated wire harness processing stems from the component itself: traditional wire harnesses are highly flexible, non-rigid and structurally unpredictable [22]. The redesign features presented in this section are conceptual enablers derived from the identified challenges and literature. They were not physically implemented or tested within this thesis and their effects on manipulation reliability, cycle time and overall production performance therefore remain to be evaluated. Consequently, the physical architecture of future cable assemblies must be fundamentally redesigned to support machine handling, automated clip insertion and non-contact sensor tracking.

5.5.1 Structural Stiffness and Controlled Elasticity

Traditional wire harnesses are engineered for manual installation, featuring high flexibility to allow human operators to bend and twist cables around tight chassis contours. However, for a collaborative robot or an autonomous mobile manipulator, this extreme deformability leads to severe path-planning and state-estimation

tracking errors [7].

Future cable designs could integrate controlled elasticity or localized structural stiffness, for example through lightweight, semi-rigid polymer backbones or flexible exoribbing along major branches of the harness. By limiting the degrees of freedom of the DLO, such features are expected to make the cable behavior more predictable and thereby simplify robotic path planning and state estimation [7]. However, these effects were not experimentally evaluated in this thesis and would require physical testing to determine their impact on manipulation reliability and cycle time.

5.5.2 Modular Segmentation and Plug-and-Play Architectures

Current automotive wire harnesses are typically designed as massive, single-piece "octopus" configurations that span the entire vehicle body. Maneuvering such a heavy, multi-branched system entirely via automation introduces extreme handling risks and physical interference constraints.

Future automated architectures require a transition toward a highly modular, segmented cable layout. By splitting a single complex harness into smaller, self-contained functional modules (such as independent cockpit, front-end and rear-chassis modules), mobile cobots can manipulate components with much smaller payloads and simpler trajectories. These independent segments can then be coupled during assembly using standardized, structural "plug-and-play" bulkheads. This modularity is expected to simplify robotic handling by reducing payloads and trajectory complexity, which could potentially reduce cycle time and the risk of line stoppages. These expected benefits would, however, require further simulation and physical validation.

5.5.3 Robot-Friendly Connectors, Guide Pins and Vision Targets

The structural design of mating connectors and fastening clips must also evolve from human-centric to robot-centric interfaces. Manual connectors often require complex tactile feedback, asymmetric finger pressure, or latching levers that are exceptionally difficult for a robotic gripper to actuate reliably. Next-generation connector architectures must fundamentally alter this paradigm across several key design principles.

The integration of mechanical guide pins and lead-in chamfers could provide geometric self-alignment features intended to guide the plug into the mating socket and compensate for minor positional offsets. The resulting improvement in robotic insertion reliability would need to be verified experimentally.

Additionally, the implementation of standardized gripping interfaces ensures dedicated, rigid flat surfaces or grooved notches are molded directly onto the connector housing. These interfaces are intended to provide more stable and repeatable

gripping surfaces for robotic grippers, potentially reducing slippage and grasping uncertainty. Their effectiveness would require further testing

Finally, the inclusion of High-Contrast Vision Targets introduces integrated optical markers, data-matrix codes, or distinct geometric patterns printed directly onto key mating boundaries. These features could provide clearer visual anchors for computer-vision systems and may facilitate automated verification of plug engagement and seating orientation.

5.6 Results from Simulation

The simulation results presented in this section are used to assess selected aspects of the feasibility of the proposed concept and its performance relative to the derived requirements.

5.6.1 System Requirements and Workstation Design

Before starting the simulation, specific operational requirements were established to ensure the model accurately represents the physical plant environment. The workstation design is based on data collected during site visits to the production facility in Gothenburg, Sweden. The current manual assembly line measures approximately 4 meters in width. This line is organized into 6-meter segments, with each segment constrained by a 60-second takt time.

The primary design goal was to develop a robotic station with the same size as the existing configuration. This compact design is necessary to ensure the proposed solution integrates into the current infrastructure without requiring significant modifications or disrupting established production workflows. The CAD layout of the current workstation is shown in Figure 5.1. All the dimensions were designed based on this blueprint.

The simulation uses the Volvo XC60 to represent the production vehicle, as it is a best-selling model and a core product of the Torslanda plant [40]. The vehicle dimensions and geometry integrated into the simulation model are based on the official technical specifications provided by Volvo Cars [41]. The XC60 has an overall length of 4708 mm, a width of 1902 mm and a height of 1651 mm. By utilizing this manufacturer data, the simulation provides a simplified representation suitable for the intended simulation assessment when modeling the interaction between the robotic system and the vehicle interior.

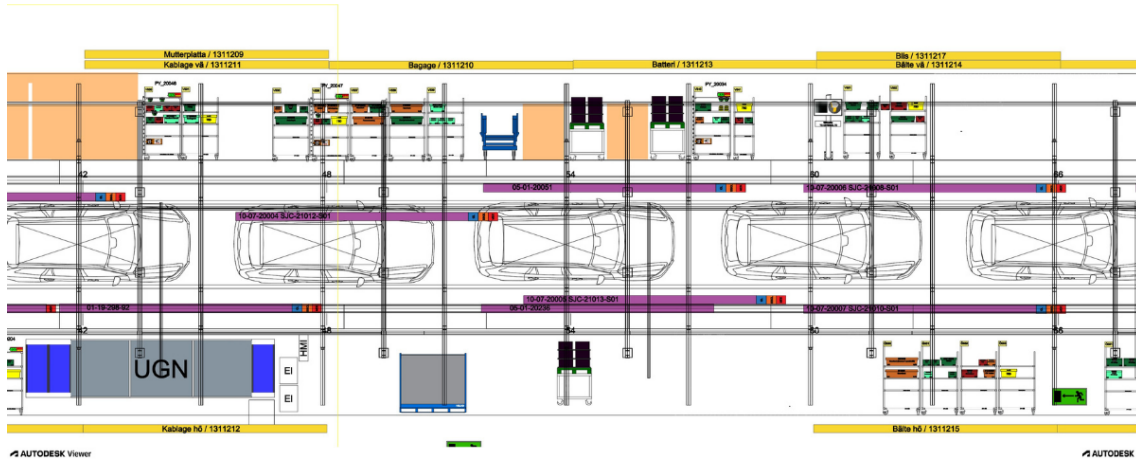


Figure 5.1: CAD layout of the current workstation.

The selection of the robotic platform was based on both the physical requirements of the assembly task and industry-standard performance metrics. Through on-site workstation analysis and internal data gathering, the harness assembly load was determined to be approximately 6 kg. While several collaborative robots were evaluated, most models lacked the necessary reach to effectively access the interior of the vehicle while mounted on an AGV.

The Rainbow Robotics RB20-1900 was chosen for this study because it offers a 1900 mm reach and a 20 kg payload capacity [32]. As previously discussed, the vehicle is a white-body car, which provides sufficient clearance for coordinated robotic manipulation. The Rainbow Robotics extended reach allows separate robots to operate simultaneously via the side openings and the rear without collision or interference. Although the 20 kg payload capacity represents an engineering surplus for the 6 kg harness load, it provides the required range of motion to perform these tasks effectively within the assembly takt time [32].

The simulation assumes that the assembly line operates exactly as it does today, without any modifications to line speed or overall flow. Changes to the conveyor speed or line configuration would influence upstream and downstream stations and therefore fall outside the scope of this study. Maintaining the existing line characteristics is also important from a cost perspective, as altering the line infrastructure would require significant investment and could disrupt established production processes.

In the real factory environment, the assembly line is slightly wider than the car body, allowing operators to walk alongside the vehicle and move at the same speed as the line. This behavior is replicated in the simulation model as shown in Figure 5.2. The area immediately outside the moving line is represented as a fixed floor surface, reflecting the physical conditions in the plant and ensuring that operator movement and accessibility are modeled realistically.

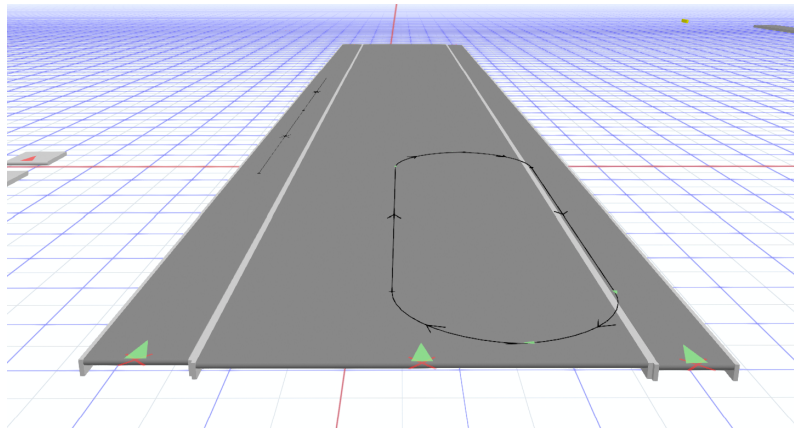


Figure 5.2: Conveyor layout

The simulation uses the same cycle time conditions as the real assembly line, in accordance with the requirements identified during the interviews in Section 5.1. The station on the line corresponds to a 6-meter segment and every segment has a takt time of 60 seconds. This results in a line speed of 0.1 m/s, which is replicated in the simulation model to ensure consistency with current production conditions.

As discussed in the case study chapter, the oven used in the existing process is excluded from the future workstation model as a conceptual assumption. The oven is currently used to increase cable flexibility and thereby support manual installation. For the proposed automated concept, it was assumed that the harness could be handled without this thermal conditioning. However, the effects of harness temperature and stiffness on robotic gripping, manipulation, routing and installation were not physically tested in this study. The feasibility of removing the oven would therefore require experimental evaluation using representative wire harnesses.

To enable continuous movement along the line, the cobots are placed on AGV platforms, as shown in Figure 5.3. This provides the mobility needed for the cobot to follow the vehicle during the installation sequence rather than remaining fixed in one position. Stopping the line would negatively affect throughput and disrupt the flow of other stations. By mounting the cobot on an AGV, the cobot can move alongside the vehicle during the modeled sequence and return toward its starting position after completing the assigned motion. The simulation was used to illustrate this movement concept, but return time and detailed cycle performance were not quantitatively measured. The cobot and AGV are intended to move back and forth on the side of the conveyor belt as shown in Figure 5.4.

In this future concept, five cobots, one corresponding to each of the five current operator roles, are proposed to operate along the moving assembly line on AGVs. This configuration reflects the current task distribution rather than a calculated minimum; determining the actual number of cobots needed would require a detailed task-time analysis of the target cycle time, which was outside the scope of this simulation. The cobots mounted on the AGVs operate at the same speed as the real assembly line, 0.1 m/s, allowing them to move alongside the vehicle without needing

to compensate for line motion. After completing its task, the AGV returns to the start position at 1.5 m/s. This speed was used as an assumption in the simulation model; however, physical human–robot safety during AGV and cobot operation was not assessed and would require a dedicated safety evaluation before implementation.

A short waiting period was included as an assumption in the simulation sequence before the next vehicle arrived. A sensor at the entry point was modeled to trigger the AGV and cobot sequence when a new vehicle entered the station. The sequence was observed to repeat consistently in the simulation; however, the duration of the waiting period and its effect on cycle performance were not quantitatively evaluated.

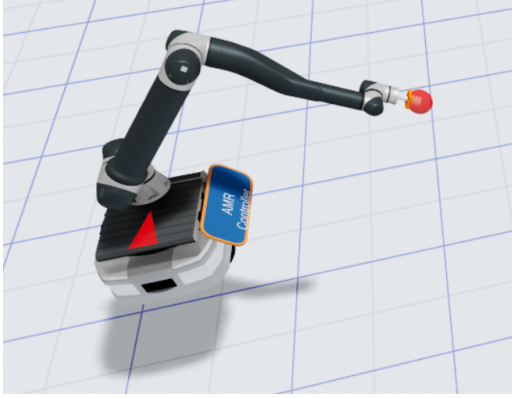


Figure 5.3: Cobot mounted on an AGV platform

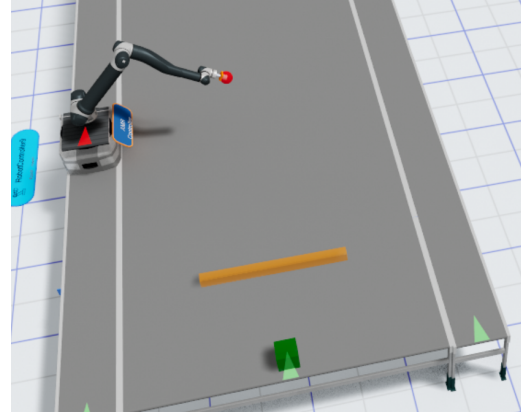


Figure 5.4: Cobot-AGV placement alongside the conveyor

To assess the layout feasibility, line-speed synchronization and motion paths of the multi-robot setup without the computational overhead of non-linear deformable physics, a stylized macro-sequence was established within Emulate3D. The simulation sequence initiates when the vehicle chassis triggers an entry sensor on the 6-meter moving line segment, prompting the front-right cobot mounted onto its respective AGV to execute a predefined path to pick up a localized custom load object. This object acts as a bounding-box dimension proxy with a rigid weight configuration of 6 kg, representing the consolidated mass of the uninstalled wire harness assembly. The cobot picks it from the conveyor of the supply line, moves it to the vehicle interior workspace through the door frame cavity and positions the proxy load onto its initial mounting baseline inside the cabin space, as shown in Figure 5.5.

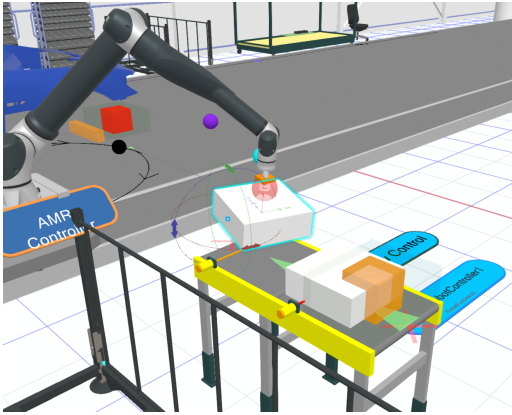


Figure 5.5: Cobot picking up the initial proxy load.

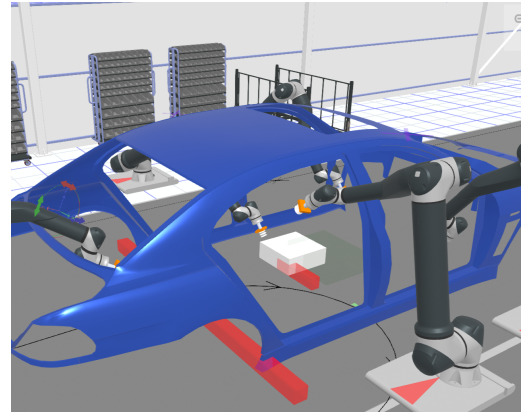


Figure 5.6: Coordinated manipulation simulation at door access points.

Once the first robot places the box inside the car, a sensor activates the other three robots at the door openings, as shown in Figure 5.6. In the simulation, these robots do not actually move real wires, but they move around the door areas to mimic the real-world time and space needed to unpack and route the cables. After a set number of cycles, the 6 kg box disappears and a new asset showing the unveiled wire harness appears inside the chassis, as shown in Figure 5.7. This visual change shows how the harness looks after it has been unpacked. Finally, the robots move back to their starting positions while the car moves down the line, which resets the system automatically to repeat the exact same steps for the next incoming car, as shown in Figure 5.8.

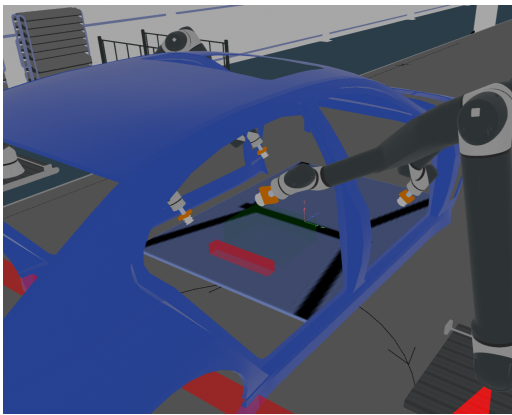


Figure 5.7: Visual representation of the unpacked wire harness.

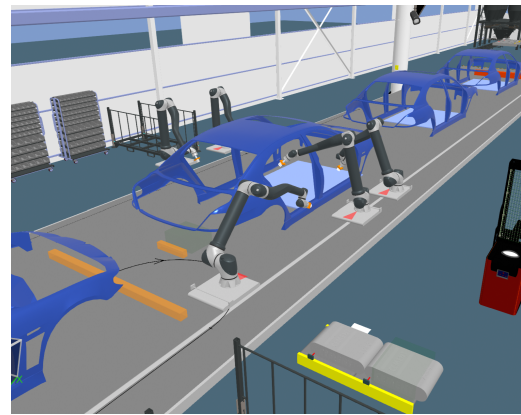


Figure 5.8: Workstation sequence during the reset phase.

5.6.2 Simulation Assessment and Limitations

The simulation was designed to assess selected operational aspects of the proposed cobot–AGV workstation concept. The results indicate that, under the assumptions represented in the model, the concept is compatible with the existing line speed, the AGVs can follow the conveyor movement without causing modeled delays, and the modeled cobots demonstrated sufficient approximate reach within the geometry of

the simulated workstation. The simulation also demonstrated the modeled movement logic, AGV paths, return movements and workstation layout without collisions or flow interruptions.

However, the simulation did not assess the full automation of cable manipulation, the performance of future vision systems, or the detailed physical interaction between cobots and deformable harnesses. These elements depend on technological advancements and robot-friendly cable redesign and were addressed conceptually rather than modeled in detail. The simulation therefore provides an assessment of layout feasibility, motion coordination, reach and line-speed compatibility within the assumptions of the digital model, while the detailed manipulation tasks require further physical testing.

The simulation does not assess the detailed physical execution of the wire harness assembly tasks. Specifically, it does not model cable deformation, gripping behavior, detailed harness routing, clip insertion, connector mating or force-controlled interaction between the cobots and the components. It also does not evaluate the accuracy or robustness of the proposed vision systems, error detection and recovery procedures or physical human–robot safety during intervention and shared operation. These aspects are therefore outside the scope of the simulation and would require physical testing under representative production conditions. Movement time, waiting time, return time, travel distance and complete cycle duration were not systematically recorded as quantitative simulation outputs. The simulation should therefore be interpreted as a preliminary visual and motion assessment of layout, approximate reach, movement coordination and line-speed compatibility rather than as a detailed performance analysis.

6

Discussion

The discussion synthesizes the findings from the empirical study, the derived requirements, the concept evaluation and the simulation results. Together, these elements provide a coherent answer to the research questions and demonstrate how the selected concept meets the identified needs of the future workstation.

6.1 Research Question Discussion

6.1.1 Which future technologies could realistically be integrated into the station?

The first research question examined which future automation technologies could realistically be integrated into the wire harness workstation within the next 5–10 years. The empirical findings show a clear distinction between technologies that are conceptually promising and those that are practically feasible in the near term.

Interviewees consistently emphasized the challenges associated with the moving-line environment, the high variation in wire harnesses and the need for safe human–machine interaction. These constraints limit the applicability of fully autonomous systems. Observations and literature study further confirmed that the deformable and unpredictable nature of wire harnesses makes real-time robotic manipulation difficult, particularly during routing tasks. This aligns with the literature on deformable linear objects (DLOs), which highlights the current limitations of vision systems in predicting cable behavior with sufficient accuracy for industrial use.

While technologies such as humanoid robots offer high flexibility and adaptability, their current maturity level does not meet the takt-time or precision requirements of final assembly at this moment in time. Similarly, full automation seems unrealistic in the short term due to the complexity of DLO handling and the need for continuous human supervision in high-variation environments.

In contrast, the findings indicate that cobots, AGVs/AMRs and vision systems supported by AI align well with both the operational and ergonomic needs of the station. Cobots are designed to support safer human–robot interaction than conventional industrial robots, and are well suited for many assembly tasks, although actual safety compliance depends on the specific application, tooling and a formal risk assessment. AGVs or AMRs are a good alternative for transportation on the assembly line and

can make cobots more flexible and move at the assembly station. Vision systems, while not yet capable of full harness manipulation, can support inspection, guidance and quality assurance.

6.1.2 What requirements must the future station fulfill?

The second research question focused on identifying the requirements that the future workstation must fulfill. The results show that these requirements fall into three main categories: operational, ergonomic and integration-related.

Operationally, the future Workstation will need to follow the takt time that is set to 60 seconds. The solution will also need to support work on a moving line as changes to the line will be hard to execute.

Ergonomically, observations revealed significant physical strain during harness routing. These findings are consistent with ergonomic literature showing that awkward postures and high-force exertions increase the risk of musculoskeletal disorders. As a result, the future workstation must reduce bending, twisting and force requirements, either through automation or improved workstation design.

When it comes to integration it is important that the solution can be tested properly before implementation in the factory. A future station should have some automation that can help humans with the hardest tasks without disrupting the line. Integrating vision system to steer cobots or support quality assurance will be important. The interviewees also highlighted the need for manual fallback options to ensure that operators can intervene when automation fails. This requirement aligns with Industry 5.0 principles, which emphasize human-centricity and resilience.

6.1.3 What concept is recommended for the next 5–10 years?

The third research question addressed which workstation concept is most suitable for implementation within the next 5–10 years. The concept evaluation compared several alternatives, including humanoid robots, exoskeletons, drones, industrial robot cells, human-centered manual assembly and hybrid automation solutions.

The results show that humanoid robots and robot dogs offer high theoretical flexibility but currently lack the precision, reliability and manipulation capability required for deformable cable handling in a moving-line environment. Industrial robot cells provide high speed and repeatability, but their need for fencing and isolated work zones makes them incompatible with shared final assembly workspaces. Exoskeletons and human-assisted workstations offer incremental ergonomic improvements but do not address the core physical challenges identified in the empirical findings, such as force-intensive clip insertion, constrained postures and complex harness routing.

In contrast, the cobot–AGV concept aligns much closer to the derived operational,

ergonomic and integration requirements. Cobots can incorporate safety functions, such as force and speed limiting, that may support operation in shared spaces. However, the need for fencing or other safeguarding depends on the robot, tool, payload, speed, task and working environment and must be determined through a formal risk assessment. AGVs enable synchronized movement with the conveyor line. This combination supports continuous flow and has the potential to reduce operator exposure to selected hazardous manual tasks. The concept also accommodates future advancements in vision-based cable manipulation and robot-friendly harness redesign, which were identified as necessary enablers for full automation.

However, to deploy the entire cobot–AGV system within the next 5–10 years may be ambitious. Several enabling technologies, particularly advanced vision systems for deformable-object manipulation and AI-based cable-shape prediction, are still maturing. A more realistic pathway is a phased implementation, beginning with a single cobot performing the most critical and ergonomically demanding task. This cobot could be mounted on a mobile platform and automate the task currently performed by one operator, while the remaining tasks continue to be performed manually. As vision systems, cobot dexterity and harness design evolve, additional cobots can be introduced to gradually expand automation coverage.

Thus, the recommended concept for the next 5–10 years is the cobot–AGV workstation, implemented through a stepwise automation strategy. This approach has the potential to provide ergonomic and operational benefits, avoid over-reliance on immature technologies and allow the system to evolve in parallel with advancements in AI, vision and cobotics.

6.2 Concept Reflection

6.2.1 Strengths

Replacing the current manual workstation with cobots and AGVs addresses several human-related challenges. First, replacing selected physically demanding manual tasks with cobots and AGVs has the potential to reduce ergonomic exposures, such as prolonged awkward postures, heavy lifting and repetitive movements. Consequently, issues like operator fatigue and restlessness, which often lead to errors that require quality checks and manual interventions could potentially be reduced. Cobots have the potential to provide consistent and repeatable task execution, but their reliability relative to manual work would need to be evaluated further. An automated workstation would still require fault detection, escalation, recovery procedures and human intervention when the system cannot complete a task as intended. Therefore, the existing Andon or escalation process would need to be adapted to support the automated cobot–AGV workstation rather than being removed.

Additionally, the combination of a six-axis motor motion from the cobot and the AGV acting as a seventh axis, along with the collaborative effort of robots working together, makes the system highly flexible. The use of collaborative robots may

enable a more open workstation layout than a conventional fenced industrial-robot cell. However, the required safeguarding can only be determined through risk assessment of the complete application. This could support a more open collaborative workstation layout, although the safety of the proposed configuration would need to be established through a formal risk assessment and physical evaluation.

6.2.2 Weaknesses

The proposed concept, while offering a clear roadmap for modernization, faces several identified weaknesses that must be acknowledged. First, the inherent complexity and unpredictability of wire harness assembly pose significant challenges for robotic manipulation. Because wire harnesses are deformable objects with complex geometries, current vision-based technologies often struggle to track or manipulate them accurately in real-time environments.

Furthermore, the technological maturity of the proposed solution remains a point of concern. Many of the advanced robotics and AI-driven quality control systems discussed are still in emerging stages. This uncertainty regarding the maturity level of these technologies makes it difficult to provide precise estimates for installation efforts, long-term maintenance and the overall economic investment required for full-scale implementation.

Another critical challenge involves the added complexity of the manufacturing system itself. While the integration of AGVs and cobots is intended to boost productivity, it simultaneously requires a more sophisticated management infrastructure. This requires a shift in the way manufacturing facilities approach human factors, system supervision and continuous adaptability of the production line.

Finally, limitations exist regarding current simulation tools, which often fail to perfectly replicate the physical, non-linear behavior of flexible components like wire harnesses. Additionally, as this study focuses specifically on a single assembly station, the findings may not be directly applicable to all areas of the factory floor without further investigation into the specific constraints of other processes.

6.2.3 Safety Considerations

The proposed cobot-AGV workstation requires safety measures for both collaborative robot operation and the movement of the mobile platforms. The collaborative safety modes introduced in the Theory chapter provide a basis for how human access and intervention could be managed in the proposed workstation. During normal operation, the system could use speed and separation monitoring to reduce robot motion as a person approaches the working area, while power and force limiting could reduce the consequences of unintended contact during collaborative operation. A safety-rated monitored stop could be used when an operator needs to enter the immediate robot working area to perform an intervention, manual fallback, or recovery task. Hand-guiding could also be used during setup, teaching, or recovery

situations, allowing a trained operator to manually reposition the cobot at a controlled and limited speed.

The mobile AGV platforms introduce additional risks because both the robot and its base can move. Access to the workstation would therefore require controlled separation between personnel and moving cobot–AGV units, supported by safety-rated sensing and defined intervention areas. If the required separation distance cannot be maintained, robot and AGV motion should be reduced or stopped before the operator enters the hazardous area. Emergency stopping must also stop the relevant automated motion and place the system in a safe state.

Following a failure or safety-related stop, automatic restart should not occur while an operator is performing recovery work. The cause of the stop should first be identified and the working area cleared before controlled restart of the cobot–AGV unit. If automated recovery is not possible, the manual fallback capability described in the requirements allows trained operators to complete the affected assembly task manually before automated operation is resumed.

These measures describe a conceptual safety strategy rather than a validated safety solution. A formal risk assessment and safety validation would be required before implementation to determine appropriate separation distances, speed limits, stopping performance, safeguarding, access procedures and recovery procedures for the physical workstation.

6.3 Human in Relation to Technology/Automation

The results indicate that in the future, with upcoming developments in technology and data science, human roles in this production could shift gradually from manual work to supervision. Currently, the main factor preventing full automation in the station is the flexibility of the wire harness. Humans are highly adaptable and their cognitive ability is what makes the process dependent on human labor today. However, continued advancements in robotics, artificial intelligence and computer vision may increase the capability of automated systems to perform these sequential tasks. In the near term, automation will most likely take over tasks that are economically justified and technically mature, while humans will continue performing complex or variable tasks and those that require dexterity and that remain challenging for robotic systems. Over a longer horizon, if the investment cost decreases and the technology becomes sufficiently capable, these remaining tasks will also be automated. In such a scenario, the human role will gradually shift from direct task execution toward supervision and handling exceptions.

An important challenge identified in this study is the relationship between product variation and automation. Increasing product variation makes automation more difficult because automated systems generally perform best when products, tasks

and processes are stable and standardized. In wire harness assembly, differences between vehicle variants, frequent design changes and complex routing increase the number of conditions that an automated system must be able to handle. Consequently, higher levels of automation require solutions that can accommodate product variation while maintaining reliable and repeatable performance.

6.4 Reflection on the methods

The research methodology employed a multi-faceted approach, combining a comprehensive literature review, qualitative interviews and direct observations. The literature review provided the necessary theoretical foundation for understanding the current trends in Industry 5.0 and the evolution of human-centric manufacturing. By grounding the study in existing academic discourse, we were able to establish a baseline for identifying the requirements of modern assembly stations.

The interviews and observations served to bridge the gap between theoretical models and the practical realities of the production floor. By engaging with industry stakeholders and observing existing processes at Volvo Cars, critical understanding into the specific operational challenges were gained, which standard literature often overlooks. These qualitative methods were essential for mapping the requirements for robotic integration, ensuring that the proposed solution remained grounded in the actual needs of the workforce and the assembly line environment.

A crucial aspect of our research involved the use of software simulations and digital modeling tools. While these tools provided invaluable insights into workstation layout, cycle times and robot-human integration, it is important to reflect on their limitations. Simulations rely on predefined parameters that may not fully capture the physical complexities of real-world materials. Specifically, the unpredictable nature of wire harnesses—including their bending characteristics, twist strength and variable geometric behavior—presents a significant modeling challenge.

Consequently, while simulations were instrumental in assessing selected aspects of the conceptual design, they may not perfectly predict every aspect of a fully automated scenario. The versatility of wire harness assembly in practice remains difficult to replicate with complete fidelity in a digital environment. Therefore, the results of this study should be viewed as a robust conceptual framework that requires further empirical testing and physical prototyping to account for these material-specific variables in a live production setting.

Several limitations affect how the results of this study should be interpreted. First, the study focused on a single wire harness assembly station at Volvo Cars. The findings are therefore strongly connected to the specific product, production system and organizational conditions of this case. While some of the identified requirements and technological challenges may be relevant to other assembly environments, the proposed concept cannot be directly transferred to other stations or plants without considering their specific conditions.

The qualitative material was also limited to a relatively small number of interviews and observations. The interviews provided detailed knowledge from engineering and technology specialists, while the observations provided practical insight into the current workstation. However, the limited number of respondents and observation periods means that the empirical findings may not represent all operator experiences, production situations, or perspectives within the organization. The derived requirements should therefore be interpreted as case-specific requirements supported by the available empirical material rather than as universally applicable requirements.

Furthermore, no cost analysis was conducted. Consequently, the study can discuss the technical and operational potential of the proposed concept, but it cannot determine whether the concept is economically viable or preferable to alternative solutions from an investment perspective. Cost, installation effort, maintenance requirements and expected return on investment would need to be evaluated before an implementation decision.

Finally, the simulation represents a simplified model of the proposed workstation and does not fully reproduce the physical behavior of deformable wire harnesses, advanced vision systems, or all interactions that could occur in a real production environment. The simulation results should therefore be interpreted as an assessment of selected aspects such as layout, movement, reach and line-speed compatibility rather than a comprehensive evaluation of the complete workstation concept. Physical testing and a pilot implementation would be required before the performance and reliability of the concept could be established under real production conditions.

6.5 Future Work

Building upon the conceptual design presented in this thesis, several avenues for future research and development are recommended. A primary next step is to conduct a pilot study or a physical proof of concept at a dedicated Volvo Cars test facility. While the simulation provided an initial assessment of the proposed AGV and cobot integration, physical trials are necessary to evaluate its performance under real-world conditions. Physical trials are necessary to address the complexities of real-world materials, specifically the handling of deformable wire harnesses under variable conditions.

Furthermore, future development should focus on enhancing AI and vision systems within the proposed workstation-integrated quality-control system. As the project identified challenges regarding the real-time predictability of harness geometry, investigating ML algorithms specifically trained for non-linear, flexible component detection would be a valuable technical advancement. This would allow the system to reach the level of precision required for fully automated quality assurance.

Finally, further studies are required to refine the "human-in-the-loop" framework. As the role of the operator evolves toward high-level management and complex

problem-solving, it will be necessary to develop comprehensive training programs and human-machine interface protocols. Future research could explore how to optimize the interaction between specialized humans and automated systems to ensure that manual intervention is not only efficient but also safe and ergonomically sound during robot failure scenarios.

7

Conclusion

In conclusion, the research conducted on next-generation wire harness assembly for Volvo Cars indicates that transitioning to a more flexible, human-centric manufacturing setup represents a promising conceptual direction based on the criteria applied in this study for the next 5 to 10 years. The empirical findings revealed significant ergonomic challenges, high variability in cable manipulation and a strong dependency on human expertise for exception handling. The requirement analysis showed that any future workstation must support shared human-robot environments, maintain continuous flow and reduce physically demanding tasks without compromising flexibility.

The concept comparison demonstrated that several emerging technologies are either incompatible with moving-line final assembly or not mature enough to handle deformable wire harnesses. Based on the derived requirements and the simulation results, the cobot-AGV concept emerges as a very promising direction for the next 5–10 years. Cobots incorporate safety functions that may support operation in shared workspaces. However, safe operation depends on the complete application and must be confirmed through a formal risk assessment. The simulation assessment provided preliminary support for the proposed layout, approximate cobot reach, movement logic and line-speed compatibility under the assumptions of the digital model. However, full cable manipulation, advanced vision-based perception and complete operator replacement were not physically tested and require further development and experimental evaluation.

The principal recommendation is therefore to implement the concept gradually rather than attempting full automation from the beginning. A realistic first step is to introduce one single cobot mounted on an AGV to perform the most critical and physically demanding task, while the remaining tasks continue to be performed manually. As AI-based vision systems and robot-friendly harness design mature, additional cobots can be added to gradually expand automation coverage. Finally, the role of human workers will naturally evolve. Manual labor will most likely shift toward higher-level responsibilities, such as managing the controls, overseeing operations and serving as the essential experts who intervene when robots fail or when complex scenarios arise. In summary, the conclusions presented here follow directly from the empirical findings, requirement analysis, concept comparison, and simulation assessment, forming a coherent basis for recommending the cobot-AGV concept while recognizing the need for further physical testing.

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A

Appendix A

A.1 Semi-structured Interview Guide

The following predefined questions were used to guide the semi-structured interviews. The order of the questions could vary depending on the discussion, and additional follow-up questions were asked when clarification or further detail was required.

A.1.1 Interview questions

1. Can you tell us about your background, and what is your current role?
2. What is most important when designing future stations, and which factors matter the most?
3. How do you think the operator's role will change in the next 5–10 years due to automation?
4. Which technologies do you consider most promising for the future of final assembly?
5. How far away do you think they are from practical implementation and are there any risks or limitations associated with them?
6. How could operators work in the future with new technologies such as AI, cobots, and similar systems?
7. How would you describe the biggest challenges in today's harness assembly station?
8. Which type of work tasks could be suitable for automation and where could humans and robots collaborate effectively?
9. What safety aspects need to be considered in such an environment?
10. What requirements does a cobot need to function in this context?

A. Appendix A

11. If you could design a new harness assembly station from scratch, what would you prioritize?
12. Which requirements do you consider most important for a future solution?
13. Is there anything we haven't talked about that you think is important?
14. What common mistakes do designers or engineers make when developing new stations?

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