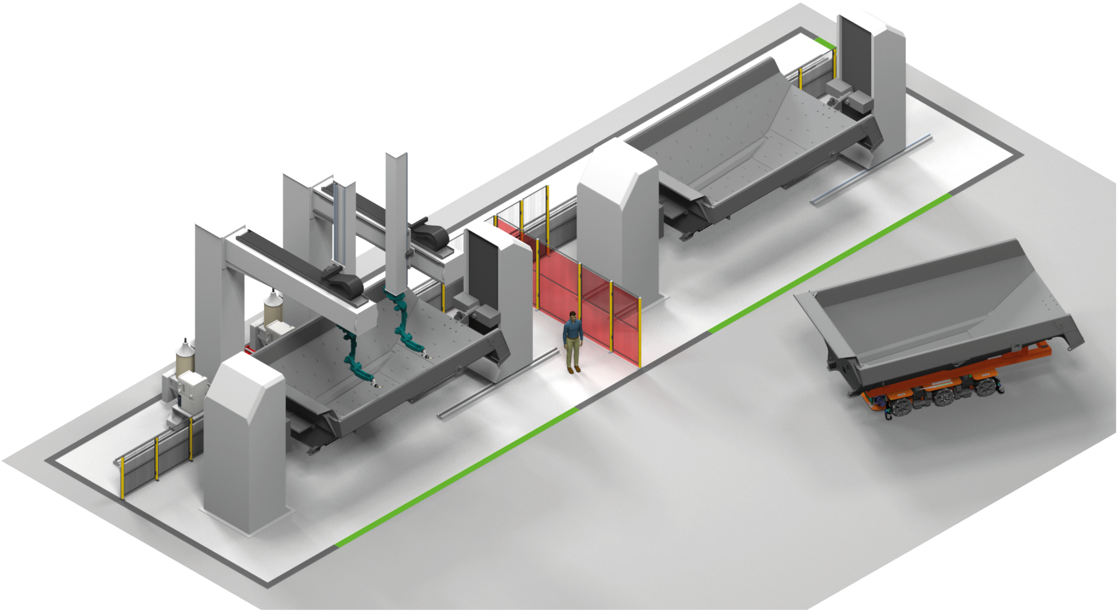

Automation of Large Low-Volume Products

A feasibility and concept study on automated welding of hauler body wear plates

Master's thesis in Production Engineering and Product Development

OSKAR VERTETICS
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DEPARTMENT OF INDUSTRIAL AND MATERIALS SCIENCE
CHALMERS UNIVERSITY OF TECHNOLOGY
Gothenburg, Sweden 2022
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MASTER'S THESIS 2022

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Cover: Visualization of the final physical production concept for automated wear plate welding, along with a proposed AGV material transport solution.

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Abstract

This master's thesis deals with the conceptual development of a production concept for automated welding of hauler body wear plates at Volvo Construction Equipment in Braås. There is a need to investigate and emphasize the potential for possible future adoptions of automated and flexible welding systems, for improved production efficiency and a better work environment. Interviews, observations, and literature studies were carried out to map the current state and identify the needs and scope. The needs and scope formed the foundation of the concept development process, which included rigorous concept generation, evaluation, and selection processes. Relevant areas and problems were further analysed and investigated to assess the technical base, test the validity of alternatives, and quantify unknowns and weaknesses. A final and indicative production concept was compiled concerning robotics and a workpiece positioner. Mainly, the production concept enables efficient, flexible, and autonomous robot welding of hauler body wear plates, significantly reducing the manual labour of welding wear plates. Furthermore, the presented production concept also provides a better and safer working environment, increased production capacity, reduced TTM, reduced risk of MSDs, increased production system flexibility, and minimisation of material handling losses.

Keywords: welding, GMAW, autonomous, positioner, robot cell, system design, manufacturing, flexible.

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The persons above who have provided valuable knowledge and experience to the project are hereon referred to as industry experts for the remains of this report.

Lastly, we would like to mention the robot and welding operators at VCE Braås, for their great input and interest in the project, ultimately providing and contributing with excellent insights and ideas.

Oskar Vertetics, Theodor Wingårdh, Gothenburg, May 2022

List of Acronyms

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

AGV	Automated Guided Vehicle
DOF	Degrees of Freedom
FCAW	Flux Cored Arc Welding
FOV	Field-of-view
GMAW	Gas Metal Arc Welding
GTAW	Gas Tungsten Arc Welding
IPS	Industrial Path Solutions
MSD	Musculoskeletal Disorder
OEE	Overall Equipment Effectiveness
PAP	Push-and-Pull
ROI	Return On Investment
TCP	Tool Center Point
TTM	Time to Market
VCE	Volvo Construction Equipment

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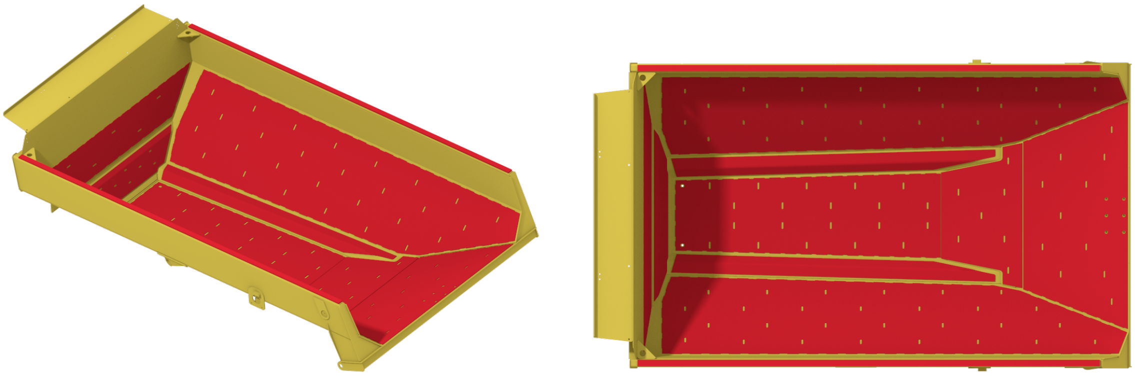
1
Introduction

1.1 Background

The articulated hauler was first introduced to the market in 1966 and has been manufactured in Braås, Sweden, ever since then. Volvo Construction Equipment (VCE) manufactures its complete range of articulated haulers in Braås, a product which is depicted in Figure 1.1. More than 850 employees work together to develop, design, test, manufacture, assemble, sell, and market articulated haulers in Braås.

Figure 1.1: Articulated hauler with the hauler body highlighted (Volvo AB, 2022).

VCE also offer a wide range of other equipment for construction, such as wheel loaders, excavators, and asphalt pavers. Most products can be customized by customers, and the articulated hauler body can for instance be equipped with wear plate kits, as illustrated in Figure 1.2. Wear plates add extra protection against abrasive wear and increase the hauler body's life expectancy.



(a) (b)

Figure 1.2: Standard body with highlighted wear plates lining the body inside.

Throughout this report, the different models of hauler bodies which have been studied are referred to as Product AH1, AH2, AH3, AH4, AH5, and AH6, in a non-chronological order. Unreleased products are only referred to as future products, as to not expose any sensitive information.

The wear plate options are welded manually in a time-consuming work process with bad ergonomics. There are about 90 variants of the hauler body, including all options for the different sizes. The variants give significant variations in the production flow regarding workload, cycle times, and ergonomics. The variations induce the need for flexibility and automation of the welding of time-consuming options in a separate after-flow to allocate all resources in the standard production flow to produce more standardised products. Furthermore, efficiently commissioning future low-volume products will require flexible welding of bodies and chassis in a separate flow to cope with varying initial demands.

The current hauler bodies also have a standard interface for suspension in workpiece positioners. Future products planned for production currently have no interface due to an entirely new hauler body design. It is not evident that the current interface will suffice to handle the new hauler bodies in production. VCE must consider changes to the interface and the hauler body design of the latest products.

1.2 Purpose

In the future, Volvo wants to weld options like wear plates in a flexible robot cell in a separate automated after-flow for improved production efficiency and work environment. The welds should be of such good quality that no manual welding is required after the process and enable direct delivery to the paint shop.

The robot cell should also be flexible enough to weld newly implemented hauler bodies and chassis to allow for flexible production while ramping up the volumes of new products. The robot cell will be a key enabler for VCEs future vision of flexible production. The increased flexibility will help handle varying demands and product customisation and lower the threshold of implementing new products in production.

The project aims to provide Volvo with a basic but complete production concept for welded options in a separate and flexible after-flow, focusing on an adjustable workpiece positioner and conceptual design of robotics. The expectation is that the finished project and concept study will serve as a part of the engineering feasibility study needed before initiating the planned re-organization of the manufacturing.

1.3 Limitations

The project focuses on presenting a digital concept with no physical prototypes or similar to be produced. The report will not cover the procurement and implementation phase in this report. Furthermore, the project should conduct no electric, pneumatic, or software design and no PLC or logic programming. The production concept should use standardised components and solutions to the maximum extent to keep the production solution cost-effective. The project also assumes that the normal operating conditions of the final concept will not be extreme in any way concerning temperature, humidity, and other factors.

The report will not cover cell calibration during commissioning. Instead, only workpiece calibration in the continuous production cycle will be considered. Furthermore, the report does not aim to present or evaluate specific models or brands of equipment that can be used to build a solution but rather to generate, evaluate and select potential subconcepts and technologies.

The project is very broad and performed under a strict timeline. There is therefore no time to go into detail in all areas discussed in the report. The project is performed at a concept stage and is therefore held at a high level of abstraction.

1.4 Problem Formulation

The thesis and project's goal is to answer the following problem formulations.

- How should the robotics in a cost-effective and flexible robot cell for welding large low-volume products be conceptually designed?
- How should a flexible workpiece positioner holding the (up to) 20-ton hauler body be conceptually designed to facilitate automated welding of large low-volume products?

Beyond that, the thesis should provide enough support and information to enable VCE to expand the engineering feasibility and concept study to cover more products, product variants, and areas.

1.5 Societal, Ethical and Ecological Aspects

Relevant aspects to consider in this project are the General Data Protection Regulation (GDPR) and the storage of personal information, mostly related to the interviews conducted in the mapping of the current state. We aim not to store or publish any personal information or images revealing identities or anything else that could harm a person or organisation. Furthermore, the project will conduct a feasibility study on a production solution that will partly replace work tasks performed by human labour, which is another relevant aspect. However, the intention is not to replace human labour with superior technology but rather to support humans and provide a better working environment. Industrial robots and technology will carry out the hard work that is unsuitable for humans concerning health and ergonomics. The human workers can then instead focus on more mentally challenging work tasks by operating the technology, which implies better overall workforce health and motivation. It is essential to state that the human workers will not be replaced by technology and instead be assigned different and more challenging work tasks.

Considering the ecological aspects, the production concept can also contribute to improved ecological sustainability. This is due to the streamlining of the welding processes and increasing the overall productivity. Ultimately, implementing the production concept will result in more effective equipment use, less consumption of energy, and less material waste.

2
Theory

The project is based on many different theoretical areas, all of which contribute to the understanding and development of a production concept, robotics, and workpiece positioner. The underlying theory supports the continuous decision and evaluation process throughout the project, ensuring correctness. This chapter will present the results of a comprehensive literature review of relevant topics to support the project processes.

2.1 Robotics

Robotics is defined by ISO 8373:2021, IDT (2021) as "the science and practice of designing, manufacturing, and applying robots". According to IEEE (2022), there are many different types of robots, ranging from consumer robots and humanoid robots to military and industrial robots. This report will focus on the application of industrial robots and will not cover the remaining aspects or areas of robotics and robots.

2.2 Industrial Robots

An industrial robot is defined by ISO 8373:2021, IDT (2021) as an "automatically controlled, reprogrammable, multipurpose manipulator, programmable in three or more axes, which can be either fixed in place or fixed to a mobile platform for use in automation applications in an industrial environment". A manipulator is considered to be a kinematic mechanism consisting of a sequence of jointed and linked arms or segments. An industrial robot includes and defines the use of a manipulator, but also a robot controller and programming interfaces, such as a pendant or external communication interface. Furthermore, the industrial robots are often used in a system context, and an industrial robot system is defined by ISO 8373:2021, IDT (2021) as a "machine comprising an industrial robot; end-effector(s); any end-effector sensors and equipment (e.g. vision systems, adhesive dispensing, weld controller) needed to support the intended task; and a task program)".

Today's industrial robots offer great repeatability, typically ranging from about $\pm$ 0,02 mm to $\pm$ 0,4 mm (Yaskawa, 2022). Furthermore, a reach of 500 mm to 4000 mm is offered as well as a payload capacity from about 0,5 kg to 1250 kg (KUKA, 2022; Yaskawa, 2022). Depending on the robot model and its robustness, robots can be floor, wall, ceiling, or angle-mounted (KUKA, 2022). Generally, a high payload capacity robot must be floor-mounted due to its own weight, since it is not constructed to take all loads implied by mounting it on the wall, ceiling, or at an angle.

2.2.1 System Design

Several parameters are important considerations when designing and implementing industrial robot systems, as Lizotte and Summers (2022) discusses. First of all, the robot's reach and work envelope are important parameters to consider. Ensuring the robot can reach all necessary positions is not the only thing to consider. The robot must also reach the positions with a correct and suitable weld angle to not suffer from bad weld quality, which ultimately will lead to increased rework and costs. Designing a system with insufficient reach to all the areas of a part or product that require welding will diminish the capabilities and also productivity. Secondly, the dimensions and weight of the parts or products to be handled and welded must be considered. The positioner must be designed to handle the total weight of the workpiece with regard to the force and torque required to translate and rotate the workpiece. Furthermore, the robot load capacity must be larger than the weight of the end-effector, or more specifically, the welding torch or gripper. This weight must also include auxiliary equipment mounted on the end-effectors or robot, such as sensors or wire feeders. To tackle these problems Lizotte and Summers (2022) emphasises the importance and strategy of designing the robot system with the largest and heaviest part that should be welded. This includes considering the current product portfolio and future products that could potentially be in the scope of the robot system.

2.2.2 Degrees of Freedom

A degree of freedom (DOF) is a way to manipulate a rigid body in space. There are six DOF in which a rigid body can move in a body-fixed coordinate system, three translations; surge, sway, and heave, and three rotations; roll, pitch, and yaw. Surge is the translation in the forward and backward direction, sway is the translation in the right and left direction and heave is the translation in the up and down direction. Surge, sway, and heave generally corresponds to translation in X, Y, and Z with respect to a earth-fixed coordinate system. Pitch is rotation around the sway axis, yaw is rotation around the heave axis, and roll is rotation around the surge axis (Pollack, 1976). All six DOF are visualised in Figure 2.1.

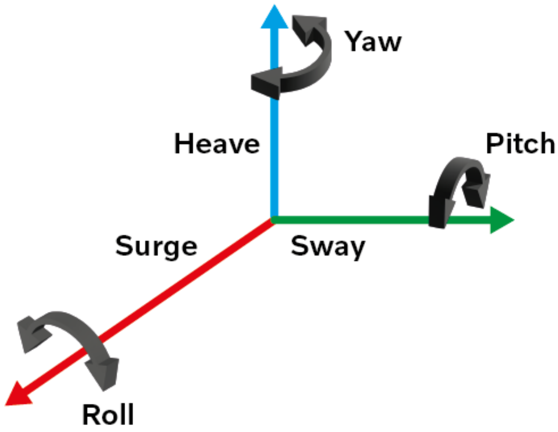


Figure 2.1: The name and direction of each degree of freedom in a three-dimensional space.

2.2.3 External Axes

Industrial robots can, beyond their own axes, be integrated with external axes to extend the reach and work envelope when the parts to be welded become larger and heavier than what the robot alone can suffice (ABB, 2013). Robots can be integrated with for instance a gantry, track, or workpiece positioner system to reach previously inaccessible weld seams and increase the work envelope to cover larger products. A gantry or track is used to transport the robot within the robot cell to reach more areas of the work object.

A welding workpiece positioner is a type of fixator and manipulator in which the workpiece is fixated. The workpiece can be fixated in different ways depending on the design of the positioner. It is used in robotic welding cells to fixate and manipulate the workpiece. The fixation improves the stability of the workpiece and makes it stable while welding. The manipulation optimises welding angles for better welding quality, reducing the need for manual after-work (Helton, Ellig, Folkmann, & Levert, 2001). The manipulation can also facilitate reaching joints that are usually not reachable if the workpiece would have been stationary (Helton et al., 2001; Weman, 2012). According to Helton et al. (2001), the positioner and workpiece can also be a part of the welding movement instead of being in a fixed position.

There are different types of positioners that allow additional DOF. One common type is with a headstock and tailstock, which attaches to each end of the work object. These are further divided into many different variants, either placed directly on the floor or attached to a shared body creating the form of a C. These positioners are therefore called C-positioners. The number of DOF in a positioner is usually minimised to the minimum amount required for easier control and lower price.

2.3 Sensors

Sensors allow robots to interpret and understand their surroundings by measuring and collecting data about the geometrical and physical environment. This allows the robots to overcome and adapt to specific situations, which induces a more flexible robot system to handle more part, product, and process variants. But, it is not as easy as just putting sensors in a robot; sensors also require excellent software support and programming to be utilised to their maximum potential.

Bolmsjö and Olsson (2005) categorises sensors used in a manufacturing setting into two categories; sensors used for controlling and optimising processes and sensors used by other machines and equipment to execute a manufacturing sequence and process. Furthermore, sensors used in the arc welding process can be divided into sensors that control and optimise the welding process and control and optimise the robot's motion and trajectory. The latter will be of focus in this report.

Bolmsjö and Olsson (2005) has also identified many potential issues essential to address and investigate before successful implementation of sensors supporting a flexible robot system for one-off or small-series arc welding manufacturing.

1. Sensors should facilitate the robot's guidance along a weld joint without requiring time-consuming and detailed programming of the entire path, including potential variations. Ultimately, the sensors must support the programming of different welding trajectories and adapt the paths to more minor variations.
2. Sensors should be able to react and facilitate the robot system to respond to environmental changes in real-time by activating alternative actions or trajectories if an obstacle blocks the nominal trajectory. Ultimately, the sensors should support and provide data for real-time robot trajectory and process adaption.
3. Sensors should facilitate the connection between a real-world model and a nominal CAD world model, supporting real-time calibration of the workpiece positions.
4. Sensors should facilitate and support the prediction of the robustness of a flexible robot welding process. Ultimately, the robustness will verify that the weld can be produced when utilising real-time adaption and robot guidance supports. This ensures that the weld can be produced concerning collision, reach, and singularities and is especially important when the experienced deviations are large.

Uprising intelligent solutions for robot welding applications utilise a wide variety of sensor technologies, providing different data sources to control the process ultimately. Various sensors are used for different purposes, and the correct technology must be selected for the proper purpose, as the performance and cost can differ significantly. Sensors can be combined to add redundancy to a system or increase the technical system capability. The recent development within part scanning and modelling sensors has enabled industries and companies to adopt robotics for one-off welding applications, ultimately increasing the system flexibility (Leath, 2018). According to ABB (2014); Bolmsjö (2005); Leath (2018), the main applications and uses of sensors in robot welding applications are seam tracking, edge detection, and part scanning. Sensor principles that enable such applications can be categorised into touch, through-arc, laser, and vision sensors (Leath, 2018). Recent research also indicates the additional use of ultrasonic, electromagnetic, vibration, and infrared sensors in robot arc welding applications (Chen, Liu, Chen, & Suo, 2022; Xu & Wang, 2021). Such sensors are commonly used to control and optimise the welding process and monitor and verify weld quality, which is out of scope for this report.

According to Chen et al. (2022) vision sensors accounts for approximately 65 % of all sensors used for seam tracking. This is because non-contact vision sensors have several advantages, such as high accuracy, fast detection, and high adaptability (Xu & Wang, 2021). However, it is also stated that through-arc sensing can be more efficient for some specific weld types. Still, it lacks the adaptability and flexibility of the non-contact type sensors.

The most optimal solution would be a sensor that facilitates seam tracking, edge detection, and part scanning while also being small not to induce accessibility issues. However, such a sensor does not exist and Bolmsjö (2005) emphasises the importance of analysing the specific need for sensors in every unique robot welding application.

As previously mentioned, there is a wide variety of different sensors offered on the market. Table 2.1 presents a comprehensive overview of the most common sensors discussed by ABB (2014); Chen et al. (2022); Leath (2018); Xu and Wang (2021).

Table 2.1: Sensor technologies identified in the literature study.

Function	Sensor Technology
Touch	Electrode Touch
	Nozzle Touch
Vision	Structured Light Laser
	Structured Light Projection
	Active Stereo
	Passive Stereo
Laser	Time-of-Flight
	Laser Sensing
	Laser Triangulation
Through-Arc	Arc Characteristics Seam Tracking

Electrode Touch Sense refers to the physical touch of the electrode and filler wire at the end of the welding torch against the workpiece (Leath, 2018). Applying low-voltage enables detection of conductive materials, either by the power supply or separate circuit. By detecting the surface of the workpiece at two or three points, the position or orientation of more superficial joints and geometries can be determined. According to Åkesson (2021), deviations ranging from 0,5 mm to 20 mm can be detected.

Nozzle Touch Sense has a similar approach, but instead of touching the workpiece with the electrode and filler wire, the weld torch nozzle is used instead. This provides better accuracy since the gas nozzle is more rigid and less prone to variations. It is harder to predict the electrode positions accurately since they will drift and vary in all directions, depending on the wear and process characteristics. However, in recent years, new functions allowing the robot to lock the electrode feeder unit have improved the Z-axis's accuracy since it is not as sensitive to clashes affecting the electrode position during the searches. Both Electrode Touch Sense and Nozzle Touch Sense require the workpiece to be roughly in the nominal position. With too large deviations, the risk is that the pre-programmed search algorithms and trajectories may not find the surfaces of a workpiece. These algorithms and trajectories should be designed concerning the workpiece variation that can be expected.

Through-Arc Seam Tracking refers to the use of through-arc sensor technology to measure the arc characteristics outputted by the power source to detect deviations in the nominal robot welding trajectory (Leath, 2018). This can be applied to weaving weld trajectories, and during the welding process, the seam edges are detected with changing arc characteristics. According to Leath (2018), this type of sensor is best suited for use in applications with longer weld seams and some variation since it is often less of an effort to adapt to the variations rather than investing in fixtures to reduce the variations. With more significant gaps and variations, the sensor can facilitate gap filling.

Cameras provide vision and images of a workpiece or tooling, including information on identity, position, and orientation. Cameras with 2D technology are great for locating parts in a plane, but it does not have the required field depth for locating parts in space. The 2D camera is therefore suitable for more straightforward applications experiencing some variability in part positioning since it has lower complexity and cost (Leath, 2018). Cameras with 3D technology allow for locating items and parts in space due to their depth of field. This technology adds complexity and costs in all aspects but provides a more significant degree of automation.

A laser can replace traditional sensor technology use in all application areas. ABB (2014) classifies laser methods into 1D, 2D, 3D, spot, line, and circle. Laser Sensing refers to using a 1D laser proximity spot sensor to find edges and is a significantly faster alternative than the touch sense sensors in edge detection (Åkesson, 2021). However, laser sensing requires a laser sensor being mounted on the welding torch, which can limit the accessibility to some extent according to Åkesson (2021) and Leath (2018). Furthermore, both Åkesson (2021) and Leath (2018) discuss the fact that laser technology may not be suitable with some materials due to the reflective surfaces and induced lousy data quality.

With Laser Seam Tracking, a 2D laser line is projected onto the seam to collect the seam profile and geometry data (Åkesson, 2021). This data is processed in real-time, allowing path correction and seam tracking. Laser Seam Tracking allows for faster cycle times than through-arc sensing but requires an external sensor being mounted on the welding torch, reducing the accessibility to hard-to-reach joints and seams (Leath, 2018). Furthermore, Åkesson (2021) discusses the fact that laser seam tracking is very accurate and does not require a weaving motion. Laser technology can also be utilised in part scanning with a 3D Laser Scanner, creating a point cloud containing millions of different surface points of the part or product being scanned.

2.3.1 Seam Tracking

Seam tracking refers to robot guidance and keeping the robot on an appropriate welding trajectory, omitting the need for complex and time-consuming programming of trajectories (Bolmsjö, 2005). Thermal influences, uneven heat transfer, material deviations, staggered edges, clamping variation, or improper part alignment often affect the fit-up and seam alignment. Still, seam tracking offers an opportunity to counter such variations and automate many welding processes (Xu, Yu, Zhong, Lin, & Chen, 2012). Some additional advantages of implementing a seam tracking solution are stated by Bjorkelund (1987) to be less stringent positioning demands of fixtures and parts and lower bad weld quality rejection rates. As previously mentioned, there are two main methods for seam tracking; arc-sensing and 2D laser (Åkesson, 2021).

Furthermore, Bolmsjö (2005) discusses the fact that the traditional seam tracking algorithms and technology only correct the welding trajectory positions in the x, y, and z-axis rather than correcting the orientation. This can be related to the lack of process execution robustness since large path deviations and re-orientation would most likely drive the robot joints into singularity or end positions. Securing robustness and allowing greater freedom in tracking more significant variations require advanced simulation and control tools (Bolmsjö, 2005). Lately, there has been an enormous improvement in the sensor technology and data processing field, which has increased the possibilities of implementing solutions for more significant deviation seam tracking while securing the robustness of robot execution.

2.3.2 Edge Detection

Edge detection refers to utilising sensors to find the edge or start position of a welding seam and trajectory, which is a means of calibrating each welding start position. Sensor technologies usually used in edge detection are touch sensors or proximity sensors (ABB, 2014). Procedures and functions for edge detection are today normally integrated into the robot controllers, power supplies, and programming software, which enable simple and quick use of edge detection in different welding applications.

2.3.3 Part Scanning

Part Scanning refers to detecting and sensing a part geometry in two or three dimensions. Such data can be used in many manufacturing applications, such as locating parts and tools and inspecting part quality or alignment. Many different systems and principle technologies for acquiring 2D and 3D part geometry data are available today and come under many other names. Bi and Wang (2010) presents different principle technologies used by such systems and classifies them into passive and active systems. Bi and Wang (2010) presents the passive systems shape-from-shading, shape-from-motion, or passive stereo vision. The active systems are laser triangulation, time-of-flight (laser pulse and phase shift lasers), and interferometry. Bedaka, Mahmoud, Lee, and Lin (2018) presents the most common principle of non-touching technologies; active time-of-flight (laser pulse and phase shift lasers), laser triangulation, structured light, and passive stereo vision. Laser scanning is a broad term that includes both laser triangulation (laser profiling) and time-of-flight (indirect and direct), with different supporting algorithms. The output of time-of-flight and laser triangulation is most commonly a point cloud, while the output of structured light and stereo vision is generally an RGB-D image.

Setting up a vision system comes with the challenges of selecting the most optimal angles and positions for acquiring valuable and high-quality data. According to Johnston (2002), several aspects must be considered to ensure a high-performing vision system adapted to the specific application. This includes speed, accuracy, measurement volume, part geometry and surface complexity, lightning conditions, and the need for real-time data analysis. Furthermore, Bi and Wang (2010) adds that the resolution, spot size, and field of view also affect the choice of the most optimal part scanning method.

2.3.4 End-Effectors

An end-effector is defined by ISO 8373:2021, IDT (2021) as a "device specifically designed for attachment to the mechanical interface to enable the robot to perform its task".

According to Bolmsjö (2014), the end-effectors can be divided into three different categories; grippers, process tools, and end-effector exchange systems. Grippers are mainly used in material handling and assembly and are gripping or holding material mechanically, using a vacuum, or using electromagnets. Grippers using vacuum or electromagnet are according to great options when dealing with flat surfaces such as metal sheets. Process tools refer to end-effectors used explicitly in different processes, such as welding torches, spray guns, and grinding tools. End-effector exchange systems add flexibility and increase the usability of a robot since it can perform different tasks with various grippers and tools (Bolmsjö, 2014).

2.4 Programming

Programmability is one of the essential features of a robot. Efficient methods and supporting platforms and software allow users to create new robot tasks quick and accurate (Bolmsjö, 2014). Programming robots ultimately comes down to defining a set of trajectories and poses a robot should reach in a specific sequence.

Bolmsjö (2014) categorises the programming of robots into two different categories; how they are programmed and where they are programmed. How they are programmed refers to the different abstraction levels of the programming language and how the tasks are described. Where they are programmed refers to the use of either online programming or offline programming. In other words, is the robot programmed using the robot and pendant on the shop floor, or is the robot programmed using dedicated software and digital models on a separate computer. Where does not implicate how, since the same programming language and structure are used in all cases. However, how can implicate where, since not all abstraction levels are possible to program using a robot pendant.

Online programming has been the most commonly used method and is still used to a broad extent. Online programming provides some relative advantages and disadvantages compared to offline programming (Bolmsjö, 2014). For instance, the programming is intuitive and direct since the actual robot system is used for programming. Furthermore, programming in a real environment means that all geometrical variations in equipment, tooling and fixtures are taken into account and compensated for. However, the robot system will be occupied during programming, which can impact the productivity of a robot system. Complex program structures involving a lot of logical commands can also be quite hard to program and maintain online.

One of the benefits of offline programming that Bolmsjö (2014) discusses is the possibility of programming the system while it is operating. This allows for less downtime during the implementation of new or updated programs, ultimately increasing productivity. Furthermore, one relative benefit is that it is easier to manage and produce complex programs due to the possibility of better program structures and documentation. The opportunity to further optimise and improve robot programs using software and machine learning is also enabled in offline programming. However, offline programming means that it is not possible to consider geometrical variances when programming. One drawback of offline programming is the need to calibrate and adapt the programs to the real environment and tolerances in equipment, tooling, and fixtures.

2.4.1 Abstraction Levels

Kihlman (2021) discusses a framework for the different abstraction levels of robot programming.

- Joint-level
- Robot-level
- Object-level
- Process-level
- Goal-level

Joint-level refers to the programming and recording of individual joint values without knowing about the Cartesian coordinate systems. This means that the robot will update the joint values without considering a specific trajectory. Joint-level programming is the lowest abstraction level since the motors are controlled for each joint individually. For instance, a programmed instruction on this level would consist of moving a set of joints a set of degrees or distances at a given time or step. The motors or drive system is then actuated accordingly to create a robotic motion.

Robot-level is the most common level in robot programming and refers to the use of trajectories and Cartesian coordinate systems. The robot can be programmed to follow a linear, joint, or circular trajectory between two points in space. Points are defined as a Cartesian XYZ position with an orientation, relative to a reference coordinate system. Working with relative coordinate systems allows for transformation matrices to be applied to frames and coordinate systems, enabling easy re-orientation of points and trajectories. The robot manufacturers generally develop and maintain the systems supporting robot-level programming, with inverse kinematics as an enabler. For instance, a programmed instruction on this level would be defined as linearly moving the robot from a defined position in space to another defined position in space. The system translates such an instruction to joint-level commands using inverse kinematics.

Object-level is the first degree of high abstraction level programming. In object-level programming, the programmer must know the geometry of the objects. Digital models are utilised to set symbolic spatial relations defining events on a geometrical level. By providing the symbolic spatial relations, the system plans how to execute the events using deterministic algorithms. The events are planned only with the spatial relations set by the programmer using the geometrical references. The system does not have any knowledge of the objects or the world. For instance, programmed instruction on this level would consist of arc welding the curve intersection between surface A and surface B with defined angles and welding parameters. The system translates such an instruction to robot-level commands by disintegrating the defined symbolic spatial relations and their position in the coordinate system. Since the system does not know about the models or world, extra care is required when determining the symbolic spatial relations to avoid clashes and reachability issues.

Process-level refers to only providing a start and end state. This includes providing predefined information such as the geometry of the workpiece, equipment, tooling, and fixtures. Tasks to be processed are specified in the form of process modules. By using its knowledge of the starting state, surrounding environment, and the world, the robot system will know by itself how to execute each process and reach the end state. For instance, programmed instruction on this level would provide a start state with a tack welded body with wear plates and an end state where all wear plates are welded. By recognising and evaluating the predefined environment and world, the system executes the tasks in process modules, such as welding a specific wear plate, to reach the provided end state. By itself, the robot system will know how to execute the tasks by examining and evaluating the predefined models, world, and behaviours. This includes automatic path planning to avoid clashes and auto-detection or importing of weld seams.

Similarly, goal-level refers to only providing a start and end state. However, the robot system understands the complete process on the goal-level and can create its definition of the world, environments, and behaviours. This level is, to date, only common in space applications.

2.5 Welding

Welding is the process of joining parts and materials, often metals or plastics. There are several different welding processes, such as spot welding, arc welding, laser welding, and friction stir welding. And according to Pires, Loureiro, and Bolmsjö (2006), the two most commonly used arc welding processes are Gas Tungsten Arc Welding (GTAW) and Gas Metal Arc Welding (GMAW). These processes rely on an electric arc being established between the electrode and the workpiece. The current passing through the arc will induce high enough temperatures to melt the metals and fuse the parts. Only GMAW will be covered in this report, as the other welding processes are considered out of scope.

2.5.1 Gas Metal Arc Welding

GMAW uses a consumable filler wire and electrode to establish an arc with the workpiece and feed the filler wire to the weld pool. In contrary, GTAW uses a non-consumable electrode to establish the arc while externally feeding a filler wire to the weld pool. Such filler metals are according to Pires et al. (2006) used when welding sheet thicknesses larger than 2 mm, and the filler wire is fed by using a roll or coil. With thinner metal sheets, only the heat is sufficient to have a strong bond between the metals. Shielding gases are also used to protect the arc, and it has according to Pires et al. (2006) an effect on arc stability, weld bead shape, and melting rate. These gases can be divided into two different types, inert gases (MIG) and active gases (MAG), and both are widely used within the GMAW process.

GMAW is the most commonly used welding process in the industry due to its many benefits compared to other processes (Pires et al., 2006). For instance, the GMAW process can be used with many different materials and sheet thicknesses. It has a relatively high deposition rate and can weld much quicker than traditional processes, making it cheaper. Furthermore, GMAW is a semi-automatic process since the wire is fed automatically to maintain a constant arc length, and there is no need to change electrodes all the time. According to (Pires et al., 2006), these circumstances make GMAW the superior choice in automatic welding applications and explicitly using it with robot systems.

Required equipment for GMAW is a power source, weld torch, electrode wire feeder, and shielding gas flow regulator. The power source provides a constant-voltage output and is connected to the feed unit and workpiece to create a closed-loop flow circuit when the arc is established.

A welding torch designed for use with robots consists of an electrode contact tube, nozzle, and handle, as Figure 2.2 illustrates. The contact tube directs to current to the electrode at the tip of the torch. The nozzle directs the shielding gas, the handle supports the gas or water cooling tubes, and the electrode guide tube and current wire. The welding torch accommodates the arc between the electrode and workpiece and directs the shielding gas towards the workpiece and weld seam. The welding torch neck can have different shapes and diameters, and they must be chosen with respect to the application. Aspects essential to consider in the choice of welding torch are welding application characteristics, material to be welded, electrode and filler-wire diameter, workpiece dimensions, single or twin setup, power source manufacturer, accessibility with regards to neck size and angles, crash box, and cable routing. The most common angles and shapes are necks with an angle of 22, 36 and 45 degrees and a special S-shaped torch neck. One should always choose the torch neck with the lowest angle possible due to the added friction when feeding wires through a tighter angle. This ensures maximal life expectancy of the equipment and reduces the cost of maintenance. Furthermore, the diameter relates to the expected duty cycle, welding current, and application characteristics. Larger diameter torch necks can facilitate higher duty cycles and welding currents and better cool the torch neck. The duty cycle directly relates to the choice of gas or water cooling, and water-cooling is typically used to fabricate heavy-duty equipment. Routing cables through the robot arm with a hollow wrist comes with several advantages. The robustness and reliability of the robot application are increased since the wires do not risk interfering with the workpiece or manipulators. Furthermore, the wear and tear are reduced with internally routed cables, increasing life expectancy and lowering maintenance costs. Offline programming of robot applications with internally routed cables is also more straightforward since the potential interference with externally routed cables does not have to be considered.

The electrode wire feeder uses a set of rollers to push the wire through the electrode feeding tubes and into the welding torch. With automated welding applications, the wire is fed from a spool or large drum to minimise the need to change the wire and induce non-value adding time (Pires et al., 2006). Furthermore, a feeding unit is usually mounted on the third robot axis to pull the wire and feed it into the welding torch via the electrode guide tube. Wire-feeders can also be placed closer to the drum if the wire is fed longer distances to create a push-and-pull (PAP) system.

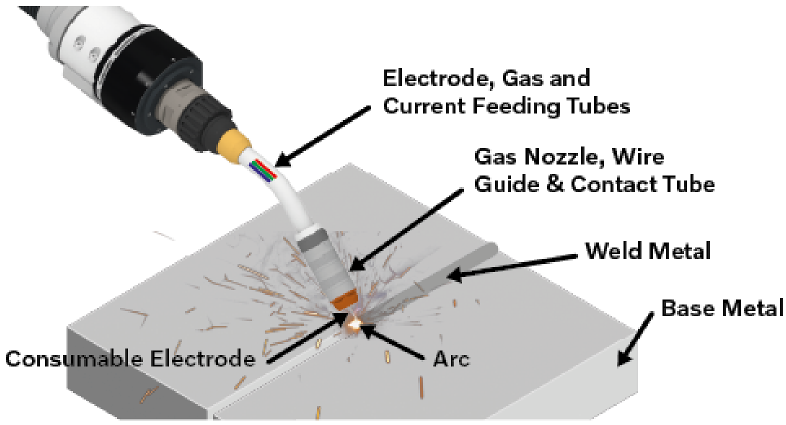


Figure 2.2: GMAW process and torch.

There are two different and commonly used electrodes, solid electrode wires and flux-cored electrode wires. Flux Cored Arc Welding (FCAW) is a process variant of GMAW that utilises flux-cored electrode wires instead of solid electrode wires (Pires et al., 2006). This yields several benefits over solid electrode wires, such as higher decomposition rates and higher duty cycles.

Another process variation of GMAW is the use of tandem or twin and multi filler-wire setups while welding. This refers to the feeding of two or multiple filler wires very close to each other, which can facilitate a higher deposition rate and welding speed (Bohme, Nentwig, & Knoch, 1996). However, one drawback is the increased total geometrical volume of the welding torch due to an extra torch needed next to the single one, which ultimately leads to the inability to reach some weld seams.

According to Weman (2016), the arc-on time factor describes the ratio between the total time the arc is established, or the total time that current is passing through the electrode, and the total welding time. This is an essential measure of efficiency, as it describes the utilisation of a welding resource concerning the total process time, including non-value added activities. Typical arc-on time factors are 20 to 40 % for manual GMAW processes, 40 to 80 % for mechanised GMAW, and 50 to 90 % for robotised GMAW (ESAB, 2022). Previous research at VCE has shown that the arc-on time factor ranges from about 65 % to 80 % in standard automated GMAW processes at their facility.

2.5.2 Automation

Automation of the welding process increases the efficiency and welding quality, improves the working environment, and decreases the ergonomic stress of the welders. According to Weman (2012), robotised arc welding comes with benefits such as increased productivity and arc-on time factor, more consistent and generally a higher weld quality, and an improved working environment.

Due to the precision and repeatability of industrial robots, it is essential to accurately position and orient components before welding. Usually, this is done either with manual tack welding or by using specific welding fixtures. By best practice, the automation of arc welding applications (GMAW) generally requires a total weld joint positioning tolerance equal to the electrode and filling-wire diameter. Meaning, that if a 1,6 mm electrode and filler wire is used, the allowed tolerance for the location of the weld joint should be $\pm$ 0,8 mm, or 1,6 mm in total tolerance (Leerink, 2017). Furthermore, Weman (2016) states that the tolerance of the location of the weld joint should typically not exceed $\pm$ 0,5 mm, or 1,0 mm in total tolerance. Lying outside of this tolerance, the arc might not be ignited and established due to poor alignment between the tool centre point (TCP) and the welding seam. However, if it is not possible to ensure the required positioning tolerances, edge detection can be utilized to find the start position. This can typically be done within a 0,5 to 20 mm range from the nominal starting position (Åkesson, 2021). This is often the case in heavy fabrication, where it is hard to maintain the required tolerances throughout the manufacturing processes due to the sheer size of all components and the immense heat transfers during welding.

Bad fit-up is another aspect to consider when automating arc welding processes. With manual welding, the human sense can detect and compensate for more minor variations in fit-up and seam gaps. To secure the welding quality in automated welding processes, sensors following the seam and providing adaptive gap-filling on the go using weaving motions can bridge smaller gaps. However, gaps exceeding a total tolerance of 0,5 mm to 1,0 mm are not recommended depending on the material thickness (Leerink, 2017). With too large gaps, the smelted metal risks going through the gaps rather than bonding the components and parts, resulting in a bad quality weld. According to the Volvo Group (2016) internal welding standard, STD 181-0004, the gap variation should not exceed 1,0 mm plus 30% of the throat size a for all quality classes. Gap variations larger than 3,0 mm are, however, never permitted. Since the complexity of vision, sensors, and intelligent solutions is often relatively high and comes with a high cost, it is almost always preferable to minimise the process variation and part-fit up using fixtures. However, fixtures and other clamping mechanisms might reduce the flexibility needed and induce a need for many fixtures and tooling that are not economically feasible.

According to Helton et al. (2001), essential aspects to consider when designing and programming robotic welding are the electrode and weld torch angles relative to the base and wall of the weld. The optimal base to torch and wall to torch relation angle is 45 degrees when welding fillet welds, with different tolerances depending on the required welding quality and penetration depth. Furthermore, other welding parameters such as wire feed speed, voltage, current, and potentially some overlaid weaving motions are essential.

2.5.3 Welding Positions

Welding positions refer to the workpiece position during a welding operation and impact the flow of the molten material. Different welding positions are generally used to control the weld pool and ensure an excellent quality weld and the required penetration profile. Generally, there are six distinguished welding positions, PA, PB, PC, PD, and PE (Weman, 2016). Additionally, PF and PG describe the vertical welding positions.

According to Weman (2016), fillet welds are usually welded in positions PB or PD but can also be welded in additional positions, as illustrated in Figure 2.3. PA is the most advantageous for ensuring the correct penetration depth and weld quality, and PB is advantageous when welding around corners.

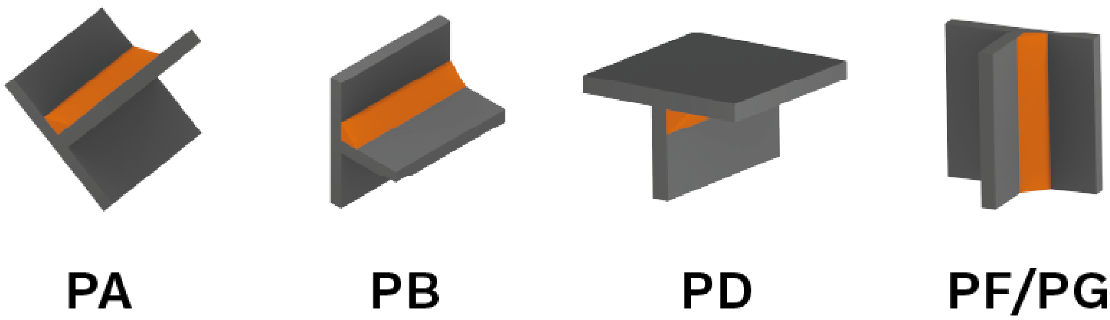


Figure 2.3: Distinguished welding positions for fillet welds.

2.5.4 Standards

Volvo Group (2016) have developed an internal welding standard, STD 181-0004, used throughout VCE to set the requirements of the welds. The welding standard applies to all steel welding with a thickness larger than three millimetres. The standard establishes five weld classes: VS, VE, VD, VC and VB, where class VB refers to the highest quality requirements and VS is a weld class for static strength.

The standard describes if certain type of imperfections are permitted or not for specific types of weld classes, and to what extent they are allowed. For instance, overlap and cold lap is controlled, and for VS and VB it is not permitted at all. For VE, VD, and VC, the overlap and cold lap must be less than 1, 0,5 and 0,1 mm respectively. Weld classes are assigned to all welds performed, and helps the operators and robot programmers to understand the weld joint requirements and significance.

2.6 Ergonomics

Ergonomics is a vast term with more meaning than the frequently used associations with comfort and correct set-up of the office chair and computer screen. Almost any aspect of human work can be related to ergonomics. Some examples are the interpretation of instructions, physical demands, teamwork, or protective gear (Berlin & Adams, 2017). According to Berlin and Adams (2017); Tahmasebi, Anbarian, Torkashvand, Motamedzade, and Farhadian (2018), musculoskeletal disorders (MSDs) are common in many industries due to unergonomic working positions, leading to illness, reduced physical ability, and early retirement. Especially manual welding requires many unergonomic positions such as bending, stretching or other static positions for more extended periods of time. Research on factors for work-related accidents for welders shows that unergonomic positions are the most common factor. Many tools and equipment have been developed to improve the ergonomics and productivity of the workers, although the most efficient way is still through automation (Tahmasebi et al., 2018). Automated welding of unergonomic positions saves personnel from early retirement and reduces work-related accidents due to unergonomic positions, often reducing lead times and improving productivity.

2.7 Automated Guided Vehicles

Automated guided vehicles, or AGVs, are electric, automated transporting vehicles. Hence no driver is needed. They are often used in industries or warehouses to transport resources between different places within the building. Depending on the needs, they come in different shapes and sizes and can be equipped with forks for carrying pallets, lifting mechanisms, and more. They can transport heavy loads and move horizontally and vertically, making them flexible. There are many different techniques for the guiding system of the AGV. The most common are buried wire or magnets-guidance systems, painted lines or laser guidance. AGVs are also equipped with sensors for detecting obstacles and prohibiting collisions (Baker, 2017).

3
Methods

To answer the project's problem formulation; various steps, methods, and analyses that must be implemented are identified. The report distinguishes Method and Implementation into two different chapters, where the Method describes the underlying theory. All steps with a general underlying theory are described in this chapter. For the implementation of the work, see Chapter 4.

3.1 Interviews

The method of identifying and evaluating the current state, needs, solutions, and criteria is on based several qualitative unstructured interviews with industry experts and employees within VCE. Due to the exploratory problem formulation, unstructured interviews were considered the best method of collecting different viewpoints without any pre-defined structure. Unstructured interviews help collect qualitative data, compared to structured interviews which help to gather more quantitative data (Bryman & Bell, 2007). Contrary to structured or semi-structured interviews, unstructured interviews do not include a set pattern of questions prepared in advance (Bryman & Bell, 2007). This allows for more in-depth answers and the possibility to ask questions that will contextualise and deepen the initial ideas on different areas.

3.2 Robotic System Development

According to Bolmsjö (2014), before investing in, designing, and implementing robotic systems, thorough project planning is required to clear all the steps needed to reach the desired results and effects. Lizotte and Summers (2022) also states that the chosen robotic cell layout and its components strongly impact the robotic system's quality, efficiency, and productivity. Therefore, adequate planning ensures excellent results considering layout, tools, and components.

Many established project planning methods aim to provide a method and framework for uniformity in the project planning process in different aspects and industries (Kerzner, 2013). However, there is no one-fit-all method. This project has reviewed and evaluated several methodologies to find the best fitting method, which is a robot cell design and implementation framework outlined by Bolmsjö (2014).

According to (Bolmsjö, 2014), the work included in a robotics system project can be divided into three different major phases; feasibility study, procurement, and implementation. Each phase is equally important to plan and execute in a structured manner to succeed in investing in a robotic system. The customer or an external partner often conducts the feasibility study. The procurement phase involves both the customer and a system integrator and its suppliers. The implementation phase is mainly performed by the system integrator and its suppliers, with support from the customer. This report will only cover the feasibility study phase.

3.2.1 Feasibility Study

A feasibility study intends to describe the background of an investment project, formulate a project aim, and set initial requirements (Bolmsjö, 2014). Furthermore, the purpose is also to seek, develop, and select different concepts to analyse the feasibility of other possible alternative conceptual solutions (Kerzner, 2013). The feasibility study will recommend the best conceptual alternative with associated benefits and costs based on the initial requirement identified.

For all investments to design and implement a robotic system, it is essential to, at an early stage, define a preliminary requirement specification list that covers the most prominent and essential parameters (Bolmsjö, 2014). Parameters and factors that are important to consider are the product range and product variations, type of work processes, production volumes, process parameters, operator needs, and motivation for the investment.

Furthermore, a more thorough analysis of the current situation of the concerned process or processes should be performed concerning the previous mapping of the production and flow to find activities with improvement potential and locate critical success criteria to evaluate the different conceptual solutions.

Kerzner (2013) discusses that a feasibility study can be conducted on two levels: summary and detail. The summary level touches upon evaluating alternative solutions, assessing cost-effectiveness, and assessing the technical base. Furthermore, the detailed level touches upon a more specific determination of the problem, analysis of the state of the art and future technology, testing the validity of alternatives and quantifying unknowns and weaknesses (Kerzner, 2013).

Part of the work included in this step will be supported by another established concept development method concerning the generation and evaluation of concepts, further described in Section 3.3.

3.3 Concept Development

For the conceptual development in this project, a process presented by Ulrich and Eppinger (2012) will be used, with small adaptations for optimal fit to this project. The full process is visualised in Figure 3.1.

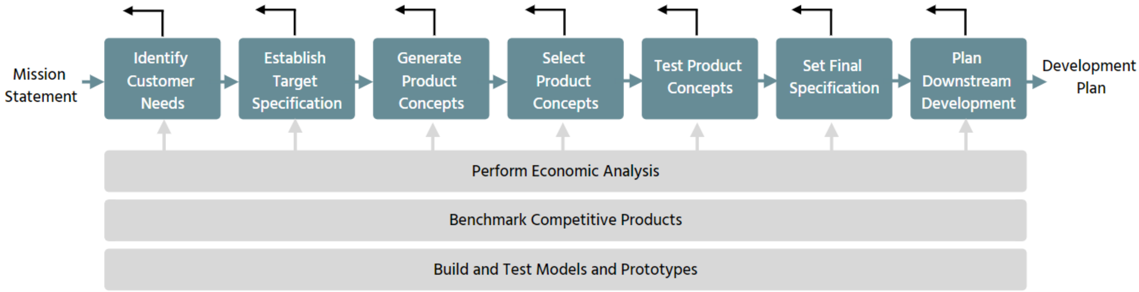


Figure 3.1: Ulrich and Eppinger's conceptual development process (Ulrich & Eppinger, 2012).

3.3.1 Identify Customer Needs

The first phase in the concept development process is to identify and understand the needs stated by the customer. In this project, the customer is VCE since their needs set the requirements and desires of the concepts. The needs could be identified through observations, interviews or analyses of raw data. The identified requirements and desires are then gathered in a requirements list.

3.3.2 Establish Target Specifications

The requirements list is complemented with target values representing the hope or expectation for each requirement or desire. The target values are used to easily measure if the need has been fulfilled and should therefore be stated in a measurable way or unit. After the testing phase, the target values are reviewed and corrected into final specifications when more constraints and trade-offs are known, possibly making some of the target values unlikely or impossible to achieve. Verification methods are also identified for the different target values and added to the requirements list to simplify the validation of whether they have been completed.

3.3.3 Generate Product Concepts

This phase in the process consists of four smaller steps. Step one clarifies the problem and breaks it down into smaller subfunctions. A significant complex problem is often challenging to approach and find solutions for. Multiple more straightforward problems where all subsolutions together form a solution for the initial big problem are much easier to work with. A Function Means Tree is used for easy visualisation of the subfunctions. In a Functions Means Tree, the main problem is divided into subfunctions. Subsolutions are then identified for each subfunction. The subsolutions are further divided into more subfunctions, and new subsolutions are added. This pattern repeats itself until the subsolutions are so simple and small enough that they can not be divided into more subfunctions. The idea is that the subsolutions to all the subfunctions in the lowest level in the tree together create a solution for the function at the top of the tree.

Steps two and three are about finding external and internal information and inspiration for the different subsolutions. Examples of external sources are benchmarking on the current market and talking to suppliers and experts. A patent analysis could also be done, finding products not on the market, inspiration for new ideas, and learning about the existing limitations when trying to develop a new idea.

In step four, the found subsolutions are organised in a morphological matrix concerning which subfunction they are solving. The subsolutions are then combined, creating possible final solutions. Some combinations are done immediately, while others are made during the process when more information is gathered. The combinations are usually done in iterations to simplify and structure the process.

3.3.4 Select Product Concepts

The generated concepts are evaluated concerning customer requirements and desires. This is done in three stages. First, a rougher concept screening procedure, an Elimination Matrix, is used. All concepts that do not fulfil any of the following five criteria are removed or paused until more information is available to say if the requirements are achieved or not.

- Main problem
- All requirements
- Is realisable
- Have a reasonable cost
- Is safe
- Not enough information

A Pugh matrix is used for the next step in the screening process. It is a powerful and effective way to screen concepts and is still easy to set up, use and understand. The concepts that enter the Pugh matrix fulfil the requirements and could be realised since they have passed the elimination matrix. Here the concepts are being compared to each other concerning the identified desires. One concept is used as a reference concept and is given a final score of zero. The other concepts are then compared with the reference concept and receive a plus, minus or zero depending on if they are better, worse or equal to that specific desire that is being compared. A plus adds one point, minus subtracts one point, and zero does not do anything. When all concepts have been screened, the total points are summed up, and the best concepts are moved on to the following screening phase. This phase is usually iterated two times with two different reference concepts to ensure that the best concepts were best independently of the reference concept.

The concepts that pass the Pugh screening process are ranked using a concept scoring method. A Kesselring matrix is often used for concept scoring since it is easy to use and contains lots of detail, complementing the less detailed Pugh matrix. The same desires as in the Pugh matrix are used but now weighed against each other to see which desires are most and less important. The desires receive a score between one and five depending on how important they are, where five is most important. The concepts are then ranked for each desire with the same ranking scale as previously used, where five is the best rank.

The rank is then multiplied by the weight of the desire, and the product of that multiplication is added as a score to the concept. All scores for each concept are summarised, and the concepts with the highest scores are considered the best ones.

After the screening and scoring process, when the concept's strengths and weaknesses are clear, the concepts are analysed to see if any improvements could be made. Concepts could be combined into new concepts or changed to improve their final score. If new concepts are found, the process starting from the screening is redone with the new concepts. Finally, the two to three best concepts are kept and further developed.

3.3.5 Test Product Concepts

The final concepts are also tested to verify that they meet the customer's needs, requirements, and expected desires or if they have to be improved. The testing phase also gives more information about the concepts which could be used for refinement or ideas to find new concepts. This step is also essential for assessing sales potential and learning what customers think about the concepts.

3.3.6 Set Final Specifications

The target specifications are revisited to see if they have been fulfilled and if the set targets are within reach. Depending on newly emerged constraints and trade-offs, some of the initial target specifications might need to be replaced with final target specifications to make them possible to reach.

3.3.7 Plan Downstream Development

In the final step in the concept development process, a development schedule contains all valuable findings found during the entire process. The schedule should state the necessary resources needed to finish the project and a strategy to minimise the development time. However, this step is not a part of this project's scope and will therefore not be conducted.

4

Project Implementation

In the preceding chapter the chosen theoretical framework is presented more in-depth. This chapter describes how each method was implemented and the workflow of the project.

4.1 Current State Analysis

Starting the project, two well-structured problem formulations, a project aim, and a project purpose were produced. This aided in identifying keywords utilised in the literature study and mapping the current state. To identify relevant material and map the current technology status that is within the framework of the project, a literature study was continuously carried out throughout the project. Keywords were chosen based on the underlying concepts found in the purpose and the problem formulation. Table 4.1 shows a selection of keywords and concepts used for the literature study, combined with logical operators to find relevant material. The database searches were conducted using the Chalmers Library service, indexing many different databases such as Google Scholar, Google Patents, Espacenet, Scopus, ISO Standards catalogue, ScienceDirect, SIS, and AccessEngineering (Chalmers Library, 2022).

Table 4.1: Selection of keywords used in the literature study.

Keywords				
industrial	robot(s)	welding	positioner	automated
flexible	heavy	headstock	tailstock	positioning
tilt(ing)	rotate	lift(ing)	robotics	calibration
intelligent	machine learning	seam tracking	sensor(s)	laser
vision	manufacturing	autonomous	metrology	3D
point cloud	quality	system	degrees of freedom	gantry
AGV	programming	GMAW	automation	ergonomics
joints	positions	arc welding	cell	design

Furthermore, to map the current state of the facility in Braås, observations and unstructured interviews were conducted on the shop floor. The general production flow and facility layout were observed, while the body manufacturing flow was studied more in detail. The studied flow started with raw sheet metal and ended with the body being welded and prepared for entering the paint shop. During this project phase, interviews were continuously held with production personnel, for instance, robot operators and welding operators, to gain extra insight and a view reflecting the workshop floor. Furthermore, experts within robot programming, welding quality, and manufacturing engineering at VCE was also interviewed to collect required additional material and information.

4.2 Problem & Requirements Target Specification

Based on the current state analysis, a problem specification was produced to highlight the key issues to cover in the project. The problem specification summarises the critical findings of the current state analysis.

A requirements specification list was compiled from the identified current state and problem specification list. The list consists of a column with identified criteria where the criteria are listed as requirements or desires depending on the importance. The requirements were complemented with columns for target values and evaluation and verification method to make the requirements measurable. This simplifies the process of verifying if the final solution fulfils the criteria.

4.3 Concept Generation

This chapter presents how the concept generation phase was executed for both the robotics and workpiece positioner parts. Furthermore, it is described how each part was broken down into subfunctions and how the subsolutions to these subfunctions form a concept.

4.3.1 Robotics

The robotics concept generation started with identifying relevant areas that had to be addressed within the project's scope, based on the problem and requirements target specification. The following concept generation framework was set and used for robotics.

1. Number of Welding Robots
2. External Axes
3. In-Cell Buffer
4. Loading of Wear Plates
5. Fixation of Wear Plates
6. Calibration of Nominal Positions
7. Seam Tracking
8. Wear Plate Design Changes
9. Weld Torch Setup
10. Program Weld Location & Parameters
11. Plan & Optimize Weld Paths

Within each area identified, solutions were generated and continuously screened. The solutions were generated based on mapping the current state, the literature study, and interviews with industry experts.

Due to the sheer amount of resulting possible combinations, four robotics concept combinations were produced based on current and common knowledge and experience of industry experts. Different themes distinguished the concept combinations to give the concepts different characteristics and possibilities. The four concepts were combined to represent all the possible combinations in the best possible way.

4.3.2 Workpiece Positioner

The workpiece positioner concept generation started with identifying the main purpose of a workpiece positioner, which was to optimise robotic welding angles and make it possible for the robots to reach all weld seams. This can also be done through manipulating the robot, but in this project, it was already given from the assignment that the solution has to include a positioner. Because of this, only that branch has been developed further, which can be seen in Figure 4.1.

The positioner was broken down into the subfunctions Movement, Fixation, Steering and Loading and Unloading. Out of these, Movement, Fixation, and Loading and Unloading are the main and most important parts of the positioner in this project. Subsolutions have been identified to the subfunctions and the subsolutions have then been divided into more subfunctions.

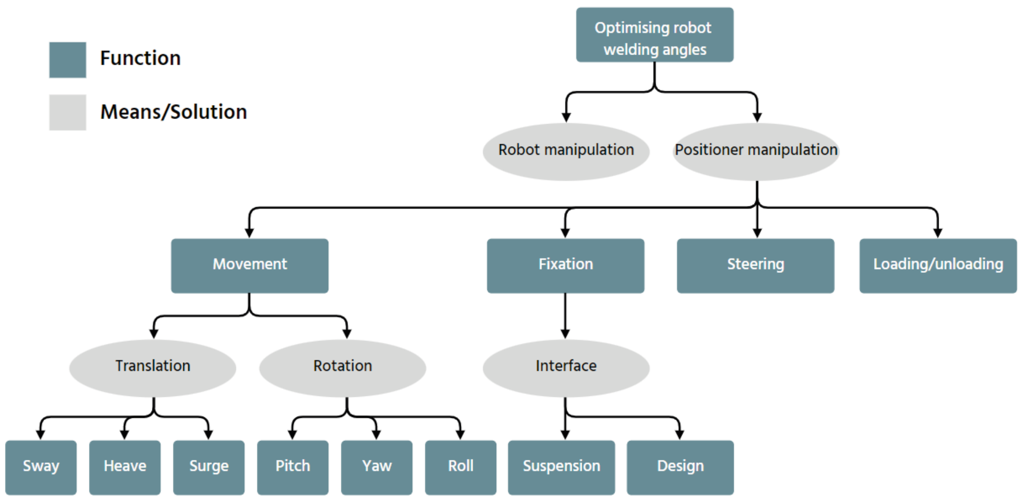


Figure 4.1: The Function Means Tree for dividing the positioner into subfunctions and subsolutions.

The last level solutions were found through patent analysis, a benchmark and discussions with industry experts. For the patent analysis, a literature study was conducted using the keywords mentioned in Table 4.1. The keywords were used alone and in different combinations to find relevant patents with solutions that could be used. The possible solutions to the functions in the last level of the tree are displayed in a morphological matrix.

For the benchmarking, the market was scanned, and existing solutions to the different last level functions were added to the morphological matrix. Current relevant solutions used in the production at VCE were also added to the matrix. Discussions with suppliers and external and internal experts were also done to inspire new sub-function solutions.

The solutions to each last level function were combined into 40 different concepts in three iterations. The concepts were combined with varying themes in mind in the first iteration. Some examples of themes used are Cheap, Product Flexibility, Safe, Sustainable, Low Maintenance, and Most Degrees of Freedom. The subsolutions were then combined, forming the concept that was believed to fulfil the different themes best. The combinations were optimised for a specific interface design subsolution in the second iteration. This was done to guarantee that all interface design subsolutions were brought to the evaluation stage. The third iteration was done during the evaluation stage where new learnings and revelations appear, making it possible to improve the concepts by swapping a sub-solution for something else or combining concepts. If one concept has flaws and another has strengths, the combination could be the best solution.

In some concepts, the body was only mounted on one end. This puts some demands on the body and its suspension system to make sure that it can withstand the pressure applied to the body. Therefore, some simple calculations and tests were performed within the concept generation phase, to ensure the feasibility of the concept ideas. The sketch of the applied forces and torque when only fixating the body in the front is illustrated in Figure 4.2

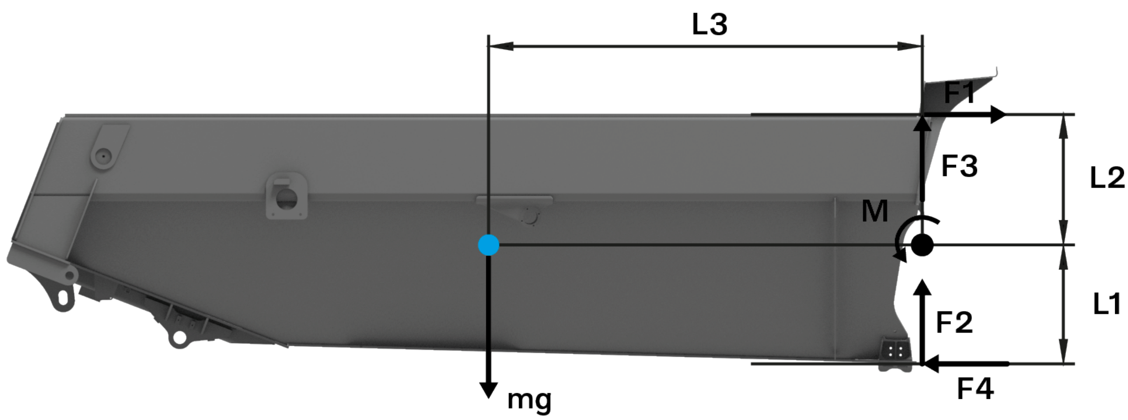


Figure 4.2: Forces and torque affecting the body when mounted on one side.

The force affecting the potential mounting points was calculated accordingly, where F was the total force, m was the maximum mass of the largest current hauler body, and g was the gravity.

$$m \cdot g = 10000 \cdot 9,82 = 98200N \tag{4.1}$$

The gravity force F equals the other horizontal forces F_3 and F_4 since they are pointing in opposite directions, as described in

$$\uparrow: F_2 + F_3 = mg \tag{4.2}$$

The vertical forces are neutralising each other according to

$$\rightarrow: F_1 = F_4 \tag{4.3}$$

The resulting torque was calculated to be

$$M = mg \cdot L_3 = 343700 \text{ Nm} \tag{4.4}$$

and by utilising the fact that

$$M = F_1 \cdot L_2 + F_4 \cdot L_1 = F_1 \cdot (L_2 + L_1) \tag{4.5}$$

the horizontal forces can be calculated to be

$$F_1 = F_4 = \frac{M}{L_2 + L_1} \cdot \frac{343700}{1,7} \approx 200 \text{ kN} \tag{4.6}$$

By taking an indicative cross-section A of the current suspension ear, the induced stress levels were validated to be feasible by calculating

$$P = \frac{F_1}{A} = \frac{200000}{640} = 312,5N/mm^2 = 312,5 \text{ MPa} \tag{4.7}$$

4.4 Concept Evaluation & Selection

This chapter presents the execution of the Ulrich & Eppinger screening process for both the robotics and the workpiece positioner. The screening process applied to the robotics was not as rigorous as the process applied to the workpiece positioner development, to allow for greater focus on production development rather than product development.

4.4.1 Robotics

The evaluation of the different robotics subfunction solutions was conducted in parallel to each other. The evaluation included an extensive literature study and interviews with industry experts and VCE employees. This formed an overall evaluation of the subfunction solutions regarding implications on essential criteria, such as cost-effectiveness, productivity, and ergonomics. The results were summarised in terms of relative advantages and disadvantages, and potential implementation approaches and issues were highlighted where applicable.

The selection of the final robotics concepts was based on a subjective evaluation with several criteria. The following criteria were included in an evaluation matrix, selected and weighted in collaboration with industry experts and VCE representatives.

- Cost
- Flexibility
- Future-Proofness
- Productivity
- Programming Complexity
- Ergonomics & Work Environment
- Maintenance/Redundancy
- Implementation Complexity

Beyond this, some subconcept solutions also required extra analysis and investigation to conclude the nature of the different subconcept solutions. The following paragraphs aim to further disclose the execution of the analyses performed within the project.

To analyse the implications of different subconcepts on productivity and cycle times, computations were performed to indicate the expected cycle times and how they are affected by different parameters. The cycle times were computed by using provided welding drawings and models, by calculating

$$\text{Cycle Time} = \frac{\sum_i \left(\frac{w_i}{w_s} + 2 \cdot r + v + s\right) w_n}{n \cdot u} + p \cdot p_t \ \forall i \in \mathbf{W} \tag{4.8}$$

where

$$\mathbf{W} = \text{Set of Welds for Each Program/Model}$$

and where w_i is the weld length, and w_n is the number of identical welds concerning clusters and symmetry. Furthermore, w_s is the welding speed, r is the ramp-up and ramp-down time, v is an estimated general via time, s is the search time, n is the number of robots, u is a utilization rate describing the balancing rate for multi-robot cells, p is the number of welding positions, and p_t is an estimated general re-positioning time for the workpiece positioner. The cycle times were computed for 14 different products and models of the hauler body.

Furthermore, the arc-on time factor for each model and product was computed by calculating

$$\text{Arc-On Time} = \frac{t_w}{t_c n} \tag{4.9}$$

where t_w is the total weld time, t_c is the computed cycle time, and n is the number of robots.

Analysing the optimal number of robots for the application, the parameters displayed in Table 4.2 and 4.3 were used in conjunction with the above calculations, set in collaboration with VCE and industry experts.

Table 4.2: Static parameters for optimising the number of robots.

Parameter	**Value**	
Single Welding Speed	0,65	m/min
Twin Welding Speed	1,1	m/min
Estimated Via Time	2	s
Search Time	4	s
Ramp-Up/Ramp-Down	1,5	s
Positioner Time	20	s

Table 4.3: Dynamic parameters for optimising the number of robots.

Parameter	Value	
Robots	X	units
Robot Utilization	Y	%
Welding Positions	Z	positions

The number of robots refers to the total number of welding robots installed and working simultaneously on the same workpiece. With multi-robot cells, synchronisation and balancing issues between robots induce blockages and wait jobs. Hence the robot utilisation was set to be either 100%, 80%, or 65%, depending on the number of robots.

The total available production time was also calculated. It was assumed that the production cell would operate in two shifts, from 06 AM to 12 AM, five workdays per week, 48 weeks per year, to provide some wiggle-room in the capacity as the planned production time can either be increased or decreased. The total available production time was calculated based on this. All planned maintenance was also assumed to be scheduled for weekends and holidays. However, there will also be unplanned stops and maintenance interrupting the operation of the cell. Therefore, using overall equipment effectiveness (OEE) data provided by VCE for one of their similar cells, an average availability was calculated to be about 65%. This measure was used to account for unplanned stops and alarms causing interruptions in production. Therefore, the available time for production was multiplied by a factor of $0,65$. Lastly, the capacity needs in production hours were calculated for automated welding of wear plates with different parameters and numbers of robots using the production volume data.

Furthermore, the possible reduction of material handling and cycle time was also calculated to evaluate the in-cell buffer subconcept solutions. The theoretical time reduction was considered together with the actual and forecasted volumes to indicate the total possible reduction.

A reachability study had to be performed to ensure the requisite reachability of the welding torch and ensure the products can be welded with excellent welding quality. The study covered two different aspects of reachability; local and global reachability.

Local reachability refers to the possibility of reaching a weld joint with the welding torch without a clash. A quantitative analysis was performed by testing whether there was a clash or not for all weld joints and documenting the required wall offset or welding angle increment required to avoid a clash between the tool and workpiece. Delmia was used to perform the analysis, using a representative weld torch, robot, workpiece, and recommended welding angles.

Global reachability refers to the possibility of the robot reaching the weld joint in a feasible configuration and pose. A qualitative analysis was performed using PTC Creo Parametric and Delmia to identify which external axes solutions could reach the entire product volume. Resolutions that did not match the entire volume were instantly eliminated, and only solutions with full global reachability were considered in the evaluation. Furthermore, possible limitations in the length of stroke for some mechanical solutions were also considered.

The welding positions required for the welding of the wear plates and future products have also been identified by analysing the products and their related welding drawings concerning weld quality, desired welding positions, and reachability. The analysis was performed using PTC Creo Parametric and identified the required welding angles and potential issues.

PTC Creo Ansys Simulation with automatically generated meshes was utilised to study the behaviour of the wear plates during lifting, handling, and loading. Potential displacements and internal stress levels were evaluated with different robotics subconcept solutions and wear plate design changes to strengthen the feasibility analysis further and address potential issues at an early project stage.

Several welding tests were performed to evaluate the current wear plate slot design and the possible base angle range. Given the welding requirements, the results could then be used to verify and validate different solutions within different areas, according to the following list.

1. Evaluated if a larger range of possible base angles to better cope with reachability issues, given the relatively low quality requirements for wear plate welding.
2. Evaluated if the slots can be welded in one go, with only one robot movement.
3. Evaluated if the slots can be welded without seam tracking, given the accuracy of the laser cutting machine.
4. Evaluated if the intermittent slot offset can be increased without inducing quality of reachability issues.

The test was performed using one of the production cells at VCE Braås, and a case-specific test piece was designed to support the evaluation. The test piece illustrated in Figure 4.3 was used, and consists of two parts welded together.

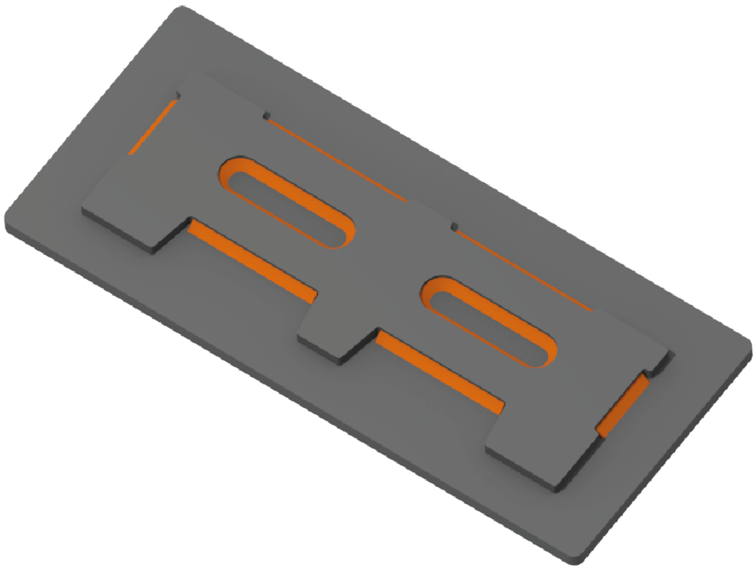


Figure 4.3: Test piece designed for welding tests within the project.

Delmia was also used to verify the weldability of the wear plate slots and if it was possible to weld them with one weld motion, in conjunction with performing physical welding tests.

4.4.2 Workpiece Positioner

The concept evaluation and selection phase for the workpiece positioner concept development consisted of three screening methods. An elimination matrix, a Pugh matrix and lastly, a Kesselring matrix. The first screening method applied was an elimination matrix, where concepts not passing this stage had significant flaws and were therefore eliminated from the process.

The next screening method used was a Pugh matrix. Since all concepts that passed the elimination matrix fulfilled the requirements, the essential desires from the requirements specification list were instead used as criteria for the Pugh matrices. In the first Pugh matrix, Concept 4, as described in Appendix A, was used as the reference concept and automatically received a zero score. This concept was used since it is very similar to an existing robot cell at VCE and did therefore give a clear impression if the other concepts were better or worse than the current solution.

In the second Pugh matrix, Concept 14, as described in Appendix A, was used as the reference concept. It was used since it is a typical, standard positioner. It gave some good perspective if the other concepts are better or worse than standard industry solutions. A Kesselring matrix was used as the next screening method.

The difference between the best and worse concepts in the Kesselring matrix was relatively small. Therefore, further analysis was conducted to separate the best concepts and choose which ones to proceed with. The relative advantages and disadvantages of using rail, AGV and overhead cranes as loading and unloading options were identified. There were no concepts left with an overhead crane, but the option was still evaluated since new concepts or changes to current concepts could be added.

Furthermore, since all bodies used in positioners are currently attached in both the front and the back, some further simulations had to be done to see if the bodies can withstand the stress and torque that occurs in a one-sided positioner. Simulations were conducted on one large and one small body to ensure that all sizes can handle the applied stress and torque. The simulations were done using a mesh size of 30 mm, an absolute sag of 10 mm and parabolic as element type. The gravity was set to 1,1 g to create some safety factor, and the body's weight was set equal to the heaviest variant available.

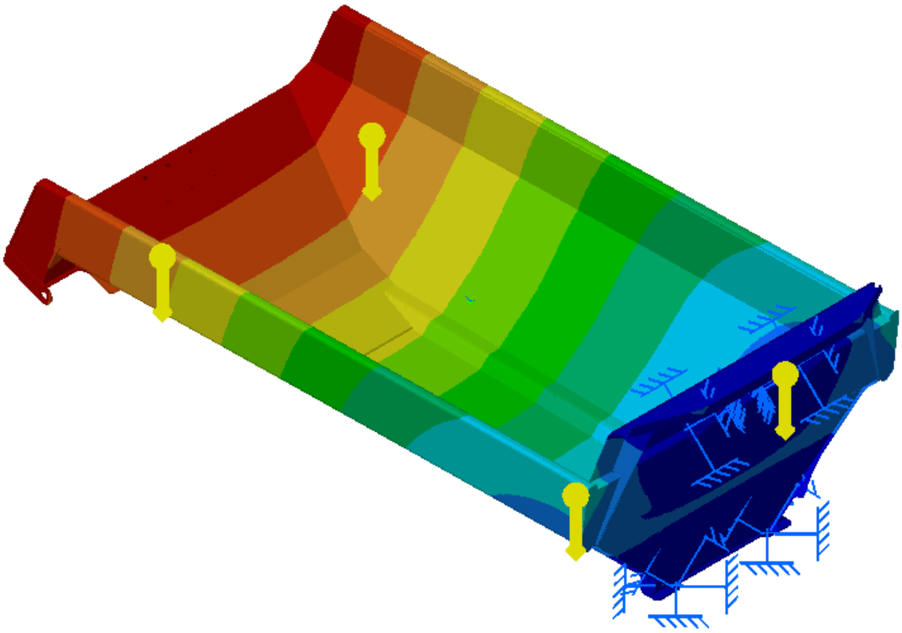


Figure 4.4: Example of a FEM simulation setup, using the optimal fixation points.

The current adapter was re-designed and modified with the workpiece positioners to enable wear plate welding without blocking weld seams or loading weld plates. The modelling was done using PTC Creo Parametric. Different mountings were also evaluated to find a good fit without restricting the access to mounting and welding wear plates.

4.5 Production Concept Modeling

After selecting a final concept for both the robotics and a workpiece positioner, the two concepts were combined to form a production concept for welding wear plates and various future products. The concept was modelled in 3D using Creo Parametric and Catia V5 to illustrate the overall concept and highlight relevant dimensions. The level of detail was set to a feasible level considering only a production concept should be delivered, but high enough to represent reality and be able to highlight potential issues at an early stage. Standard components from e.g. Bosch Rexroth and Axelent were imported and used in the production concept model. Discussions with industry experts were held to validate the mechanical design's feasibility and iterate and further improve the concept.

A rough investment calculation was performed, including Return On Investment (ROI) and payback period, to provide a first insight into the economics of the suggested investment. Budget prices provided by suppliers and previous quotes to VCE on similar equipment were studied to set a feasible investment cost. The net return on the investment was then calculated by utilising the running costs of human welders versus robot welding. The standard costs used were 600 SEK/h for man time and 1200 SEK/h for machine time. For quantifying the reduction of work required between manual and robot welding, a factor of 8 was calculated for the wear plate welding. For all other welding, a factor of 5 between the manual welding and robot welding time was used. The net reduction of man-hours and increment of machine-hours were used to calculate the net savings using the standard costs over the life expectancy. The ROI was then calculated as

$$\mathrm{ROI} = \frac{\text{Net Savings}}{\text{Investment Cost}} \cdot 100\% \tag{4.10}$$

Furthermore, the payback period was calculated as

$$\text{Payback Period} = \frac{\text{Investment Cost}}{\text{Net Savings}} \tag{4.11}$$

Beyond presenting the concept with all its components, a programming and production preparation method was also compiled. The method and vision were based on the solutions for the robotics programming and optimisation subfunctions and developed in conjunction with industry experts.

5
Results

Developing and designing a production concept and robot cell for large low-volume products is a complex engineering challenge. Many different areas have to be analysed and investigated, and this section covers the project results. For the final production concept result, refer to Section 5.6. In the preceding sections, essential partial results from the supporting research and analysis are presented to understand better the choices and selections made to compile the final production concept.

5.1 Current State

The current state of the wear plate welding process and other relevant information mapped during the project are presented in this section.

5.1.1 Production Flow

In the current production flow, illustrated in Figure 5.1, the welding of wear plates is conducted in the same flow and with the same resources as the rest of the products. Long cycle times for manual welding of wear plates block resources such as personnel and workpiece positioners for a long period, and the normal flow of products without customer options is disrupted. To partly solve the blocking issue, the most time-consuming wear plate options are welded in another facility located about three kilometres from the main facility before it returns to the main facility and the paint shop. This frees up more resources in the manual welding sequence, but such an external material flow is not ideal. The optimal solution is to weld all wear plate options in the same facility, facilitating a more efficient material flow.

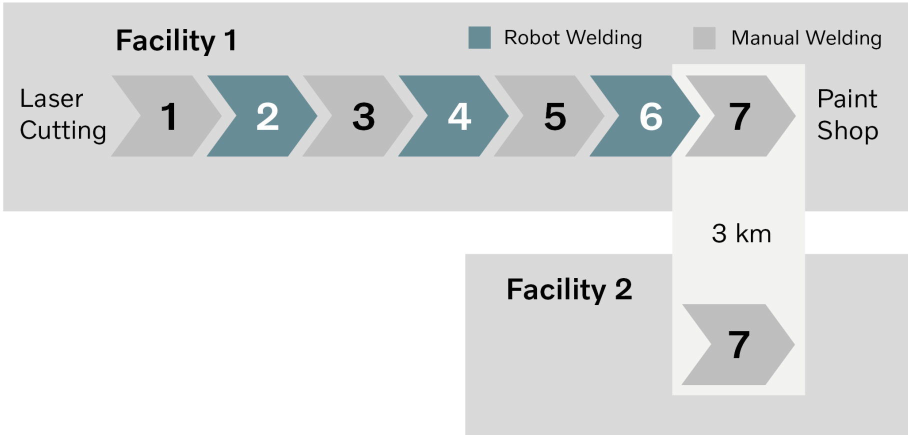


Figure 5.1: The current hauler body production flow.

The body production starts with manual tack welding of laser-cut metal parts in Station 1 to form the front and back panels of the body in specially designed fixtures. Robots then weld the tack-welded parts in Station 2. After welding, they are mounted on an assembly fixture, and together with other laser-cut metal parts, they are tack welded together to form the body's structure in Station 3. This structure is then transferred to Station 4, where it is arc welded by robots. After the welding, the body is suspended in a workpiece positioner at Station 5 to tack weld additional components to the body structure. Robots thereafter weld the body and the components in Station 6 before moving on to the final manual welding in Station 7. During final manual welding, welders correct quality issues from previous stations and weld seams that are not reachable by robots. The welding of wear plates is also conducted in Station 7, parallel to the final welding of the bodies. But, this is only the case for the standard, less time-consuming wear plate kit. Due to the extensive work needed for the heavy-duty wear plate kit, the body is instead transported to another facility for welding wear plates after it has been finished welded in Station 7 at the current facility. About 15% of all bodies fitted with wear plates are transported to another facility for manually welding the wear plates. This is to not block a positioner and resources in the standard flow and final welding area for long periods. The body production ends with the body being inspected by an independent auditor before it proceeds to the paint shop. Figure 5.2 displays an overview of the production layout regarding the production flow.

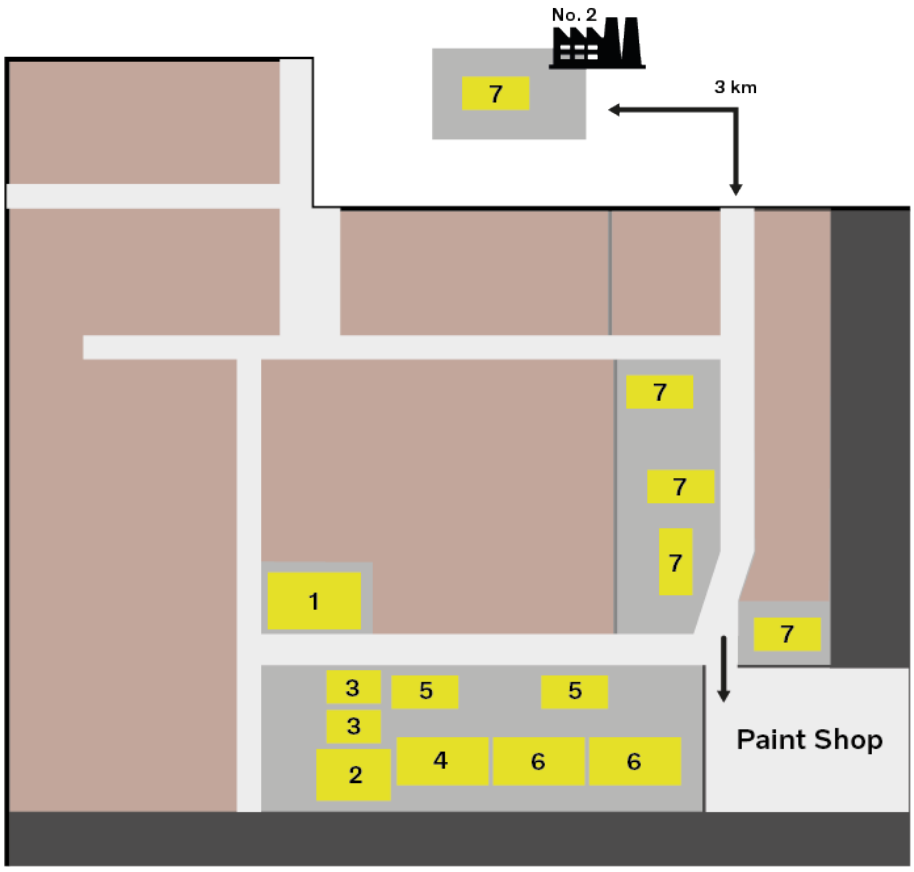


Figure 5.2: The current production layout.

5.1.2 Production Process

There are two different variants of the wear plate kits, standard and heavy-duty kits. The standard wear plate kit consists of 9 or 12 laser-cut metal plates welded on the inside of the hauler body. The heavy-duty wear kit consists of 18 or 19 laser-cut metal plates welded on the inside of the hauler body. The kit content size depends on the hauler body model, whereas the larger models have additional wear plates to protect the front of the hauler body. Figure 5.3 illustrates an example of a wear plate kit.

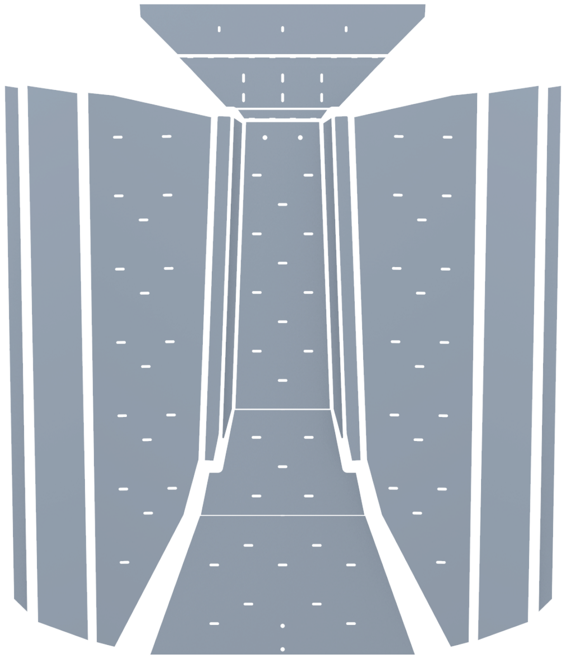


Figure 5.3: Example of a wear plate kit consisting of 16 different wear plates laid out, ultimately lining the inside of a hauler body.

The size and weight of the different wear plates included in the kits differ. This will be an essential factor when analysing the loading and tack welding of the wear plates in the hauler body and analysing the body's fixation. Also, the welding method of the wear plate kits differ, where some joints are welded intermittently, and some joints are welded full seam. The quality requirements of the welding joints are relatively low, where a throat thickness of between 4 and 5 mm is required with the VD welding class requirement. There is no requirement for penetration in the welding of wear plates. All parts subject to welding consist of Hardox 450, abrasion-resistant steel with good bendability and weldability (SSAB, 2022). The individual wear plate weight ranges from 4,0 kg to 475,7 kg, and the plate thickness from 8,0 mm to 16,0 mm. The total wear plate kit weight ranges from 697,7 kg to 2600,4 kg. The total body weight, including wear plates, ranges from about 4 300 kg to 17 000 kg.

The cycle times for the current manual welding of wear plates differ and range from 6 hours to 26 hours. According to welders and production technicians, the tacking time has been estimated to correspond to about 25% of the total cycle time. VCE has performed no time studies on this, which falls out of this project's scope. Due to the time-consuming process, the standard flow and resources for the final welding of bodies are blocked.

The current manual process induces significant ergonomic stresses and strained working positions for an extended period, as Figure 5.4 illustrates.

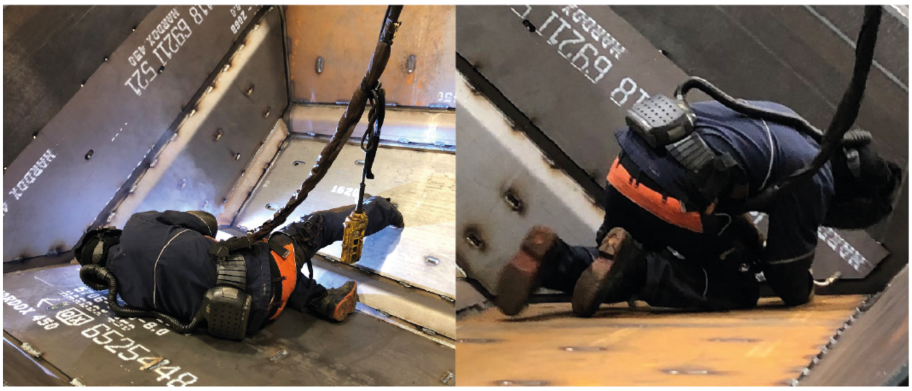


Figure 5.4: Examples of unergonomic working positions in the manual wear plate welding.

Due to the time-consuming work and welding required to finish welding a workpiece, welders can spend up to 26 hours in a bad working environment and unergonomic working positions. During welding, unergonomic working positions are unavoidable, and most of the time, the welders either sit on their knees and lean forward or lay on the ground. This puts a tremendous amount of ergonomic strain on their bodies, and the risk of injuries and long-term MSDs is much more significant.

Currently, the wear plates are, as mentioned, welded manually. A manually controlled head and tailstock type workpiece positioner manipulate the hauler body. The hauler body is lifted into the workpiece positioner using a semi-automatic overhead crane and suspended in the workpiece positioner. The wear plate kit is delivered using a forklift. The wear plates are produced in-house using a laser cutter or supplied from an external partner before being stocked in the warehouse and logistics centre. The parts cut in their laser cutting machine cannot exceed 6,0 in length and 2,0 m in width; all other larger wear plates and components have to be outsourced. The wear plates are lifted and positioned in the hauler body using an overhead crane. Due to the process and material variation, sometimes a force between 500 N to 10 000 N is applied to ensure total flushness between the hauler body and wear plates. This is done by either using crowbar, standing on the wear plate, or placing a 1-tonne weight on the wear plate using an overhead crane. The wear plate is then tack welded with force applied, to set and fixate the geometry. After tack welding is done and the geometry is set, joints are welded according to drawings and specifications. During the tack welding and welding process, hammers, compressed air, and grinders are used to continuously remove dirt, potential weld slag, and welding spark, which can negatively affect the quality and gaps.

5.1.3 Production Volumes

The production volume of the wear plate options makes up for a certain percentage of the total body production volume. The average production volume of wear plate welding is about 300 units per year. More detailed production volume data has been provided and used throughout this project, but it cannot be fully presented in the report. The data indicates a required capacity of at least six standard wear plate kits per week and an average of one heavy-duty wear plate kit per week.

Furthermore, according to Table 5.1, a forecast of the capacity needed for other products has been produced based on predicted sales data by VCE. With this data, it will be evident how long the production concept will suffice in handling both the wear plate welding and future product welding before the production concept needs to be expanded. Since the production concept should also be able to handle future products during the ramp-up phase, the future capacity needs to be considered. The capacity need will be met with the remaining capacity of the production concept after deducting the capacity required for wear plate welding.

Table 5.1: Forecasted yearly capacity needs for products subject to robot welding in the production concept, excluding wear plate welding of current products.

Year	Yearly Capacity Need
2023	42 units
2024	90 units
2025	140 units
2026	230 units
2027	400 units
2028	625 units
2029	850 units
2030	1150 units
2031	1450 units

5.1.4 Process Variations

Due to the large size of the parts and products, it is hard to maintain the required tolerances in cutting, welding, and bending processes. Furthermore, the heat input will also be more significant during welding due to the large fabrication size, which induces variation in the dimensions of the hauler body. VCE has not performed any process variation analysis based on empirical methods of hauler body fabrication. They do currently not have sufficient data to conduct such a study. Instead, they heavily rely on real-time correction for handling the variations experienced. They build and tack-weld the bodies, measure, then do the final welding and measure again. Based on the measurements before and after the final welding, they can track variations in the processes in real-time and feed it back to the subsequent procedures to compensate for potential deviations. However, this means that the compensation can only be applied to the next hauler body fabricated, which requires continuity in the compensation loop and material variations.

5.1.5 Robotics

VCE Braås has more than 15 robot cells in their facility, mainly consisting of robot cells for welding and painting. The most prominent robot manufacturer with in-house cells is Yaskawa, with the most cells installed. But ABB, Kuka, and IGM also have robot cells installed at VCE Braås. When implementing new robotic welding solutions, VCE is responsible for all programming of the welding trajectories for the body. The contractor and supplier are responsible for all other programming of the robotics, such as automatic program detection, main job, part loading cycles, tool changing jobs, service jobs, start points, and tracking, cleaning and reference jobs using sensors, vision, and scanners.

Due to the variations in the manufacturing processes, VCE currently uses electrode touch sense or laser proximity sensors for locating and calibrating all weld seam starting positions. This is a time-consuming process, and there is some time to save by incorporating other sensors, vision, and measurement technologies, to simplify the measurement and calibration process further.

VCE has offline and online programming incorporated into its production preparation and execution process. The amount of online program maintenance and fine-tuning programs concerned with changes each month corresponds to about 50% of the total program time. The total time spent on online reprogramming relates to about 5% of the production time. Offline programming is also time-consuming. In the future, VCE desires to decrease the workload required for offline programming and eliminate the need for online programming, both in implementation and production execution. The overall identified production preparation process, including offline and online programming, is illustrated in Figure 5.5.

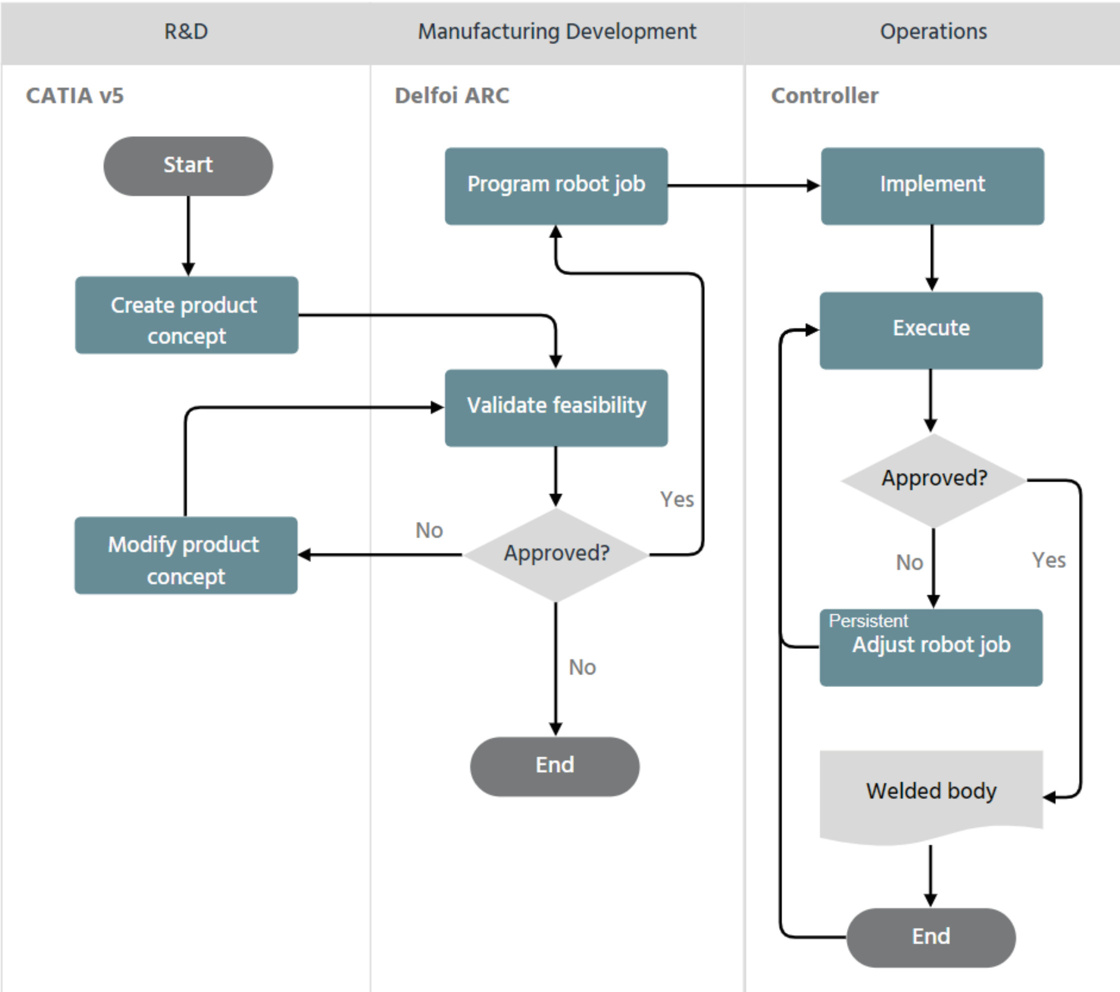


Figure 5.5: The current infrastructure of production preparation.

5.1.6 Workpiece Positioner

Table 5.2 displays different parameters of the current workpiece positioners in relevant robot cells. The most prominent existing positioner is the IGM positioner, with a length of 7000 mm, width of 4400 mm, and a maximum weight of 8 tons, but without tilting and lifting functions. If VCE plans to build bigger or heavier products than this in the future, the current positioners need to be replaced to handle the size and weight. The current time to unload and load current workpiece positioners manually with an overhead crane equals 10 minutes.

Table 5.2: Parameters for positioners currently in use at VCE.

Positioner	**Length**	**Width**	**Maximum load**	**Lift**	**Rotation**	**Tilt**
Motoman 1	7000 mm	3900 mm	8000 kg	1050 mm	360 °	-20/+23 °
Motoman 2	7000 mm	3900 mm	8000 kg	1050 mm	360 °	-20/+23 °
IGM	7000 mm	4400 mm	8000 kg	0 mm	360 °	0 °

5.1.7 Interface

VCEs current interface used to attach the bodies to the positioners consists of a head and tailstock. The bodies are suspended in the front and chute, with the front of the body mounted to the headstock working as the master side and controlling the manipulation. The chute of the body is attached to the tailstock, working as a slave unit, following the moves made by the headstock. Two ears on the front of the body align with two slots on the headstock. The ears and slots are then fixated using two horizontal locking pins pushed in with pneumatics.

For the tailstock, an adapter is bolted on the chute side of the body. The adapter consists of a resting pin where the other end of the pin rests on two cylinders on the tailstock, creating a cradle. The body's weight pushes the pin down on the cylinders. The two cylinders beneath the resting pin help reduce the friction when the body is being rotated. When the wear plate is placed on the body, the mounted resting pin on the chute needs to be removed to place the wear plate closest to the end of the chute. The body is placed on the ground instead of attached to the positioner. This attachment point of the resting pin poses an obvious problem for automatic welding of this specific wear plate. It needs to be fixed to automate the welding process of the wear plates fully.

5.1.8 Facilities

VCEs current facilities are not ready to handle larger or heavier products. The current overhead cranes are designed for carrying 10 tons. If bodies heavier than 10 tons are to be manufactured, the cranes need to be upgraded or replaced with another in-house transporting system capable of heavier weights.

The gates out of the factory might also have to be enlarged for larger products to fit and be able to ship out the finished dumpers. There is also a possible need to expand the factory for more space for the new robot cell if the space is too small. All relevant facility dimensions are presented in Table 5.3.

Table 5.3: Current facility dimensions to consider during the concept development.

Feature	Width	Height	Clearance
Gate 1	4,5 m	4,5 m	-
Gate 2	7,0 m	4,5 m	-
Gate 3	4,5 m	4,5 m	-
Overhead Crane	-	-	9,1 m
Ceiling	-	-	12,0 m

5.2 Problem Specification

During the mapping of the current state, several problems or problem areas could be identified concerning the project's scope. The issues identified and future needs form a problem specification, which is used as input to the requirement specification.

- Welding of wear plates is time-consuming and blocks resources needed for other operations in the standard flow.
- Welding of wear plates induces unergonomic and strained working positions.
- The current production facility and robot cells are not designed to handle future hauler bodies concerning the weight and size.
- Material and process deviations create variations in the part fit-up.
- With bad fit-up and not sufficient calibration, time-consuming online reprogramming is frequently required to reach the desired weld quality.
- The current wear plate design induces some hard-to-reach seams for robot welding and the seams are not optimised to be welded with robots.
- Searching and calibration of all welding start positions are performed at once for every workpiece position. The thermal contraction and expansion for each weld will affect these positions during the cycle.
- The current interface at the back of the body will have to be disassembled to fit one of the wear plates.
- Problematic to fixate the wear plates correctly during tack welding. Not good enough positioning create a chain reaction since it will affect the position of surrounding wear plates.
- The same width and thickness are used for flat bars on all models, which induce significant gaps and the need for several weld layers on smaller models.

5.3 Requirements Specification

The complete requirement specification list produced is presented in Appendix B. The requirement specification list includes elements such as performance, work ergonomics, and functions, and only covers relevant aspects which can be validated at a conceptual level.

5.4 Concept Generation

This section describes the results from the concept generation phase, conducted after setting a target requirement specification for both the robotics and the workpiece positioner.

5.4.1 Robotics

The resulting, generated and screened subconcepts are presented as a morphological matrix in Appendix C. For each subfunction, between three and eight subconcepts have been generated and screened, resulting in 9 953 280 possible robotics concept combinations. This means that all combinations cannot be generated.

Based on the morphological matrix and discussions with experts, four main concepts for robotics are produced with the following themes, presented in more detail in Appendix D.

- Low Tech

- Medium Tech
- High Tech
- Innovative

The concepts are evaluated, and a final recommended robotics concept is chosen.

5.4.2 Workpiece Positioner

The full morphological matrix with all identified subsolutions is presented in Appendix E. The total amount of combinations in the morphological matrix was 50 577 408, making it impossible to generate all of them. As shown in Appendix A, about 40 concepts with different themes were combined and generated based on the morphological matrix.

5.5 Concept Evaluation & Selection

This section describes the results from the analyses and evaluations to motivate a selection and compilation of a final production concept.

5.5.1 Robotics Evaluation

All subfunctions and solutions included in the morphological matrix must be further investigated and analysed to evaluate and select a final robotics concept. The investigation and analysis expose the different solutions and their relative advantages and disadvantages. The evaluation also maps potential issues that may arise upon implementation and aim to provide support on how to attack these.

The findings for each subfunction and solution will in this section be presented and motivated before proceeding with selecting a concept based on the findings. The relative advantages and disadvantages identified for the different subfunctions and solutions included in the morphological matrix are presented in Appendix F. The following sections will provide the results from the supporting analyses performed and conclude the information gathered from the literature study and discussions with industry experts.

5.5.1.1 Number of Welding Robots

The following list of feasible subconcept solutions generated reveals the robotics concept can include a different number of robots. The relative advantages and disadvantages of the solutions are summarized in Table F.1 in Appendix F.

- 1 robot
- 2 robots
- 3 robots

The number of welding robots directly relates to the nominal ideal cycle time and the required production capacity. The computed cycle times for the wear plate welding are shown in Table 5.4.

Table 5.4: Computed ideal yearly production capacity needs and estimated arc-on time factor, calibrating all joint start points individually.

	Capacity Need	**Arc-On Time**
1 robot	735,09 hours	71,7 %
2 robots	436,46 hours	60,3 %
3 robots	381,78 hours	46,0 %

This assumes that precisely all weld joints are calibrated precisely using a start point search. However, according to Section 5.5.1.6, this is unnecessary, and it will be more efficient to calibrate each wear plate as a workpiece instead of all separate weld joints. Since the search time accounts for about 10 to 20% of the total time, calibrating as a workpiece can significantly reduce cycle times. Instead, the resulting cycle times and arc-on time factors presented in Table 5.5 will be achieved with a more suitable calibration method.

Table 5.5: Computed ideal yearly production capacity needs and estimated arc-on time factor, calibrating each wear plate as a workpiece.

	Capacity Need	**Arc-On Time**
1 robot	612,98 hours	86,0 %
2 robots	360,58 hours	73,1 %
3 robots	314,35 hours	55,9 %

Furthermore, with only calibrating the workpiece, the resulting search and calibration time will be about 5 minutes for a complete wear plate kit cycle. More efficient calibration methods and technologies may be possible, but the effect of such a choice on the cycle time can at this stage be considered to be negligible. Therefore the ideal computed cycle times in Table 5.5 will be referred to for wear plate welding for the remains of this report. The robot welding programs which do not include wear plates or the possibility to calibrate the workpiece the same way will take all start point searches into account.

Furthermore, the total planned production hours are 4140 hours per year. Accounting for unplanned stops, the available time for production is 2691 hours. It is evident that even with one robot, the production concept will more than suffice in the capacity needed for welding wear plates. As desired, this provides some left-over capacity to produce the predicted future capacity need of new products in the pipeline. Based on the expected production volumes of future unreleased products in Section 5.1.3 and the computation of cycle times for future products, the number of years the cell can suffice in handling the required demand is presented in Table 5.6.

Table 5.6: Computation of whether the cell will meet the capacity demand for wear plate welding and other future planned products or not.

Year	1 robot	2 robots	3 robots
2022	Yes	Yes	Yes
2023	Yes	Yes	Yes
2024	Yes	Yes	Yes
2025	Yes	Yes	Yes
2026	Yes	Yes	Yes
2027	Yes	Yes	Yes
2028	No	Yes	Yes
2029	No	No	Yes
2030	No	No	No
2031	No	No	No

Based on this information, it can also be noted that the number of robots has a limited impact on how future-proof the robot cell is. One robot will cover the production capacity demand until 2027. Adding one robot will only add one year to the expected capacity coverage in each case. But, to add redundancy to the system and mitigate risks related to robot break-downs and maintenance, it could be beneficial to add a robot to secure operation.

Furthermore, it is crucial to identify the required welding positions to compute the expected cycle times accurately. The welding positions necessary have been determined to be six positions for the welding of wear plate kits. The welding positions have been estimated to be 12 positions for future products, based on the product design and current automated welding of similar products.

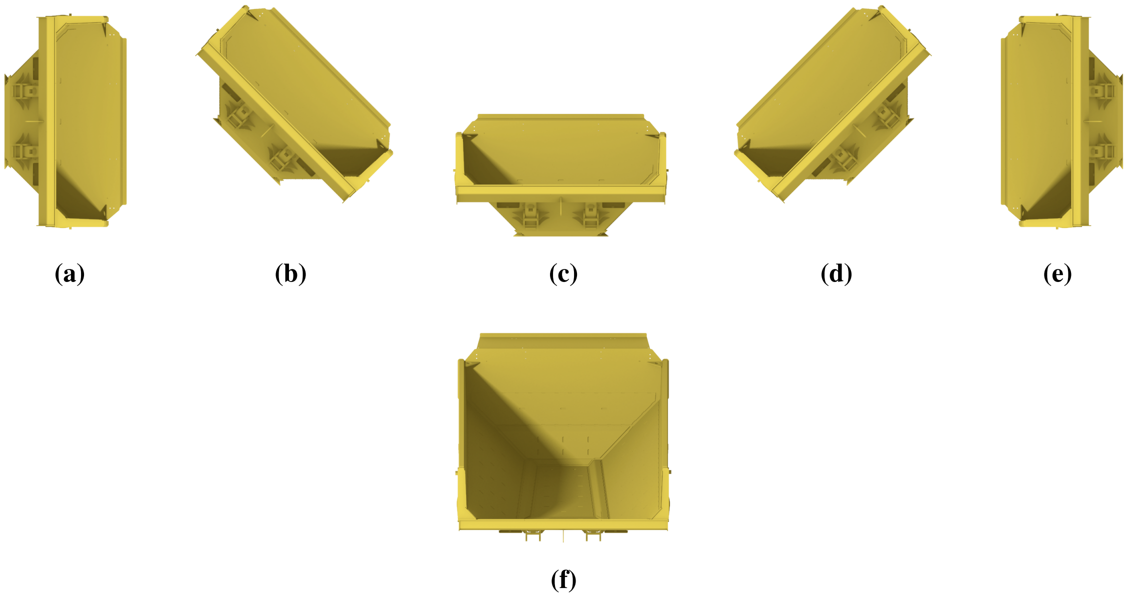


Figure 5.6: Required welding positions for wear plate welding. (a) 90° rotation and 0° tilt. (b) 45° rotation and 0° tilt. (c) 0° rotation and 0° tilt. (d) -45° rotation and 0° tilt. (e) -90° rotation and 0° tilt. (f) 0° rotation and 20° tilt.

However, some welds cannot be welded in the PA or PB positions. These are located in the front of the hauler body, as Figure 5.7 illustrates. Four different solutions have been identified.

1. Rotate the body 180° upside down and weld with a robot from below.
2. Weld with a robot in PD position.
3. Weld some weldments manually in PD.
4. Remove the concerned wear plates from the wear plate kit.

Rotating the body and welding with the robot below means that a separate robot on a track that can access the inside of the hauler body from the inside is required, which is not very cost-effective. Therefore the first alternative is out ruled. The manual welding can be performed in conjunction with the tack welding of the wear plates. However, it is desirable to weld the weldments in PD for total adaptability even though it is not recommended due to the precise process control required in an automated environment. The impact of welding it manually can be measured in the ratio of weldments welded. The need for welding in PD or manual welding accounts for about 5,5% to about 8,5% of the total weldment. Even though 0% is a desire set in the requirement specification list, the requirement of less than 10% in manual welding is met with this approach, excluding tack welding. This assumes no other manual welding is required. The last feasible alternative remains to be the exclusion of these specific wear plates in the wear plate kits, since there is minimal wear on the plates in the front.

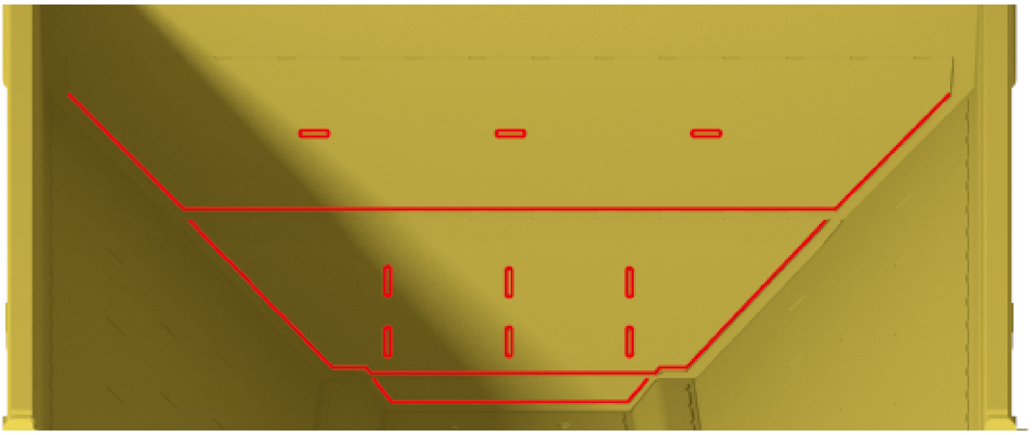


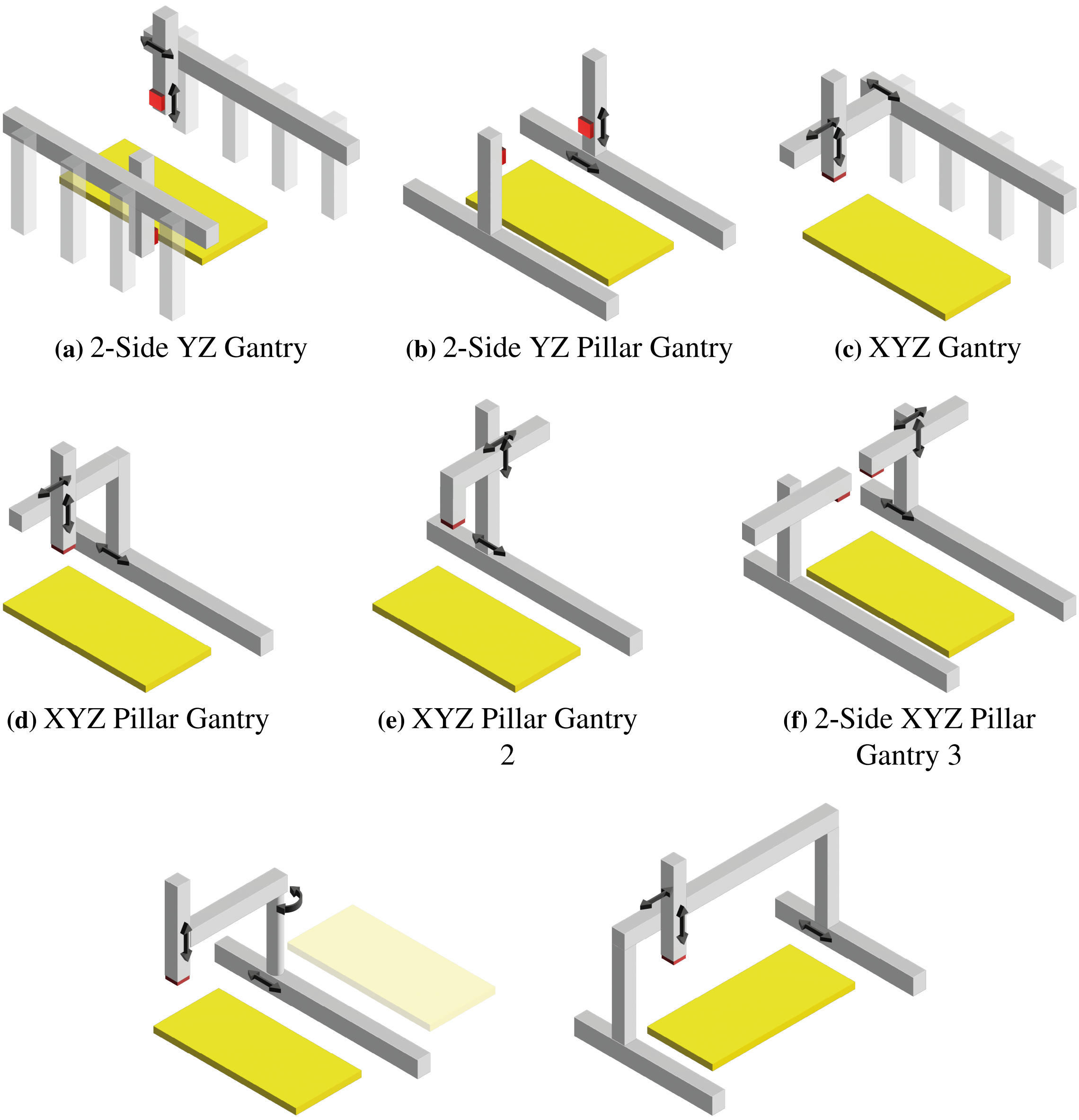
Figure 5.7: Wear plate weldments not fully reachable in PA or PB, given the possible workpiece positioner solutions.

5.5.1.2 External Axes

The following list of the feasible generated external axes solutions reveals the robotics concept can include different solutions for external axes. The relative advantages and disadvantages of the solutions are summarized in Table F.2 in Appendix F.

- 2-Side YZ Gantry
- 2-Side YZ Pillar Gantry
- XYZ Gantry
- XYZ Pillar Gantry
- XYZ Pillar Gantry 2
- 2-Side XYZ Pillar Gantry 3
- XYZ Pillar Gantry Rot Z
- XYZ Overhead Gantry

The different solutions generated are further illustrated in Figure 5.8. Talking to experts, pillar gantry has seen an increase in later years due to the less steel required and the price of steel.



(a) 2-Side YZ Gantry

(b) 2-Side YZ Pillar Gantry

(c) XYZ Gantry

(d) XYZ Pillar Gantry

(e) XYZ Pillar Gantry 2

(f) 2-Side XYZ Pillar Gantry 3

(g) XYZ Pillar Gantry Rot Z

(h) XYZ Overhead Gantry

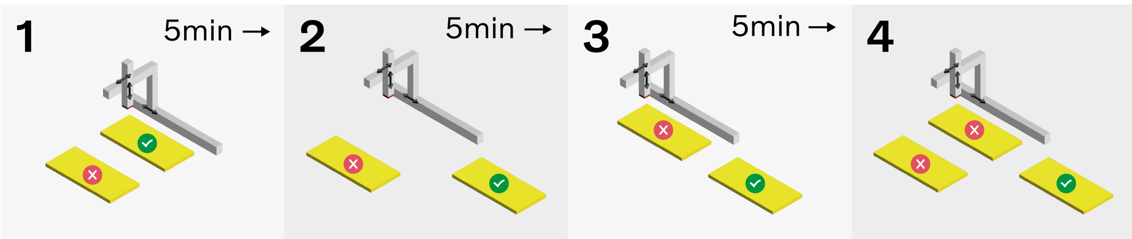
Figure 5.8: Generated and screened concepts for external axes with an articulated robot, mounted on each red square. (a) 2-Side YZ Gantry. (b) 2-Side YZ Pillar Gantry. (c) XYZ Gantry. (d) XYZ Pillar Gantry. (e) XYZ Pillar Gantry 2. (f) 2-Side XYZ Pillar Gantry 3. (g) XYZ Pillar Gantry Rot Z. (h) XYZ Overhead Gantry

5.5.1.3 In-Cell Buffer

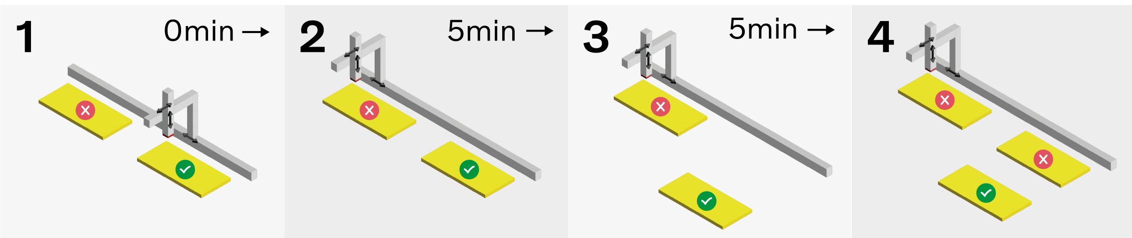
The robotics concept can include different solutions for in-cell buffers, as the following list of the feasible generated in-cell buffer solutions reveals. The relative advantages and disadvantages of the solutions are summarized in Table F.3 in Appendix F.

- None
- 1 unit
- 2 units

Integrating in-cell buffers in a robot cell helps minimise handling time and cut cycle time. The idea is to directly load the hauler body or product into the cell workpiece positioner, allowing for manual work and tack welding in the same positioner as the robot welding is conducted. As described in Section 5.1.6, the current time for unloading and loading similar workpiece positioners and products is 10 minutes, meaning the time for loading is 5 minutes, and the time required for unloading is 5 minutes. Figure 5.9 shows the different work procedures and movement of products required in the different cases, where the red cross indicates a non-finished product which can be only tack welded. The green checkmark indicates that the product has been finished welding. Figure 5.9(a) show that the body can be lifted and placed directly in the robot cell rather than first placing it in an external intermediate buffer. This means that 5 minutes of pure handling time can be eliminated each cycle and that 24,7 hours of handling time in only wear plate production can be eliminated each year utilizing in-cell buffers. Similarly, 33,4 hours of handling time can be eliminated only in the production of future products, per the forecasted volumes. The total handling time reduction corresponds to about 3% of the previously calculated available production time.



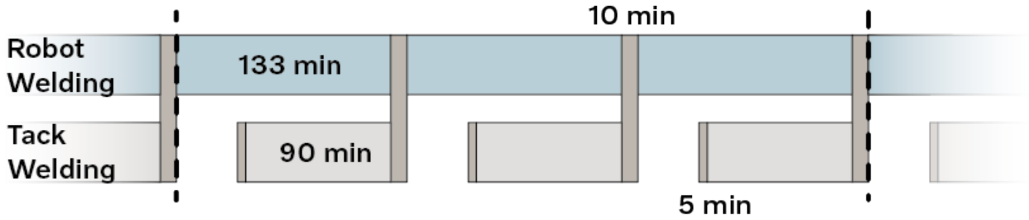
(a)



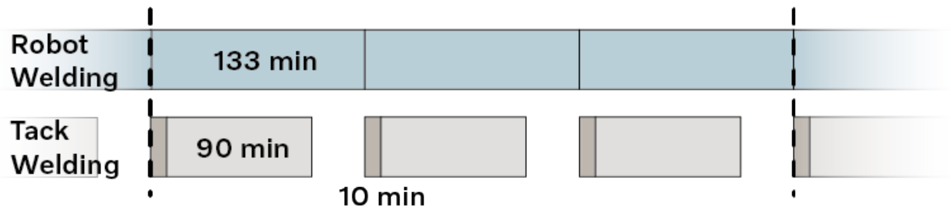
(b)

Figure 5.9: Loading and unloading procedure with (a) no in-cell buffer and tacking station outside of the cell, and (b) one in-cell buffer and tacking station inside of the cell.

Furthermore, apart from eliminating handling time, in-cell buffers reduce or eliminate the robot waiting times during loading and unloading. Depending on if the robot welding is blocked or starved during production, different time savings can be achieved. According to Figure 5.10, the cycle time can be reduced by 10 minutes if the robot welding takes longer than the tack welding process.



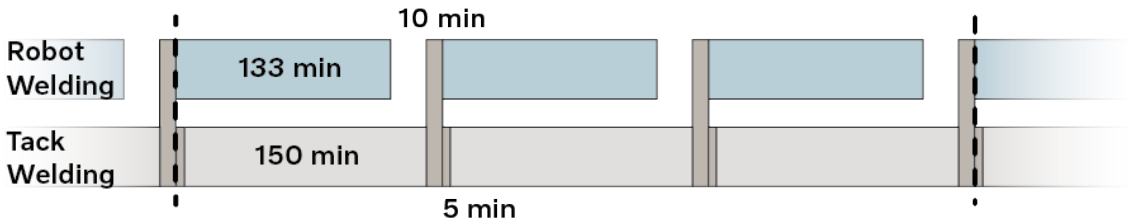
(a)



(b)

Figure 5.10: Production schedule with a longer robot welding time than tack welding time, with (a) no in-cell buffer and an ideal production time of 429 minutes, and with (b) one in-cell buffer and an ideal production time of 399 minutes.

Similarly, according to Figure 5.11, the cycle time can be reduced by 5 minutes if the robot welding takes a shorter time than the tack welding process. Therefore, the reduction in scheduling times is related to whether the robot welding is blocked or starved over time.



(a)

(b)

Figure 5.11: Production schedule with a shorter robot welding time than tack welding time, with (a) no in-cell buffer and an ideal production time of 495 minutes, and (b) one in-cell buffer and an ideal production time of 480 minutes.

Based on the computed cycle times, production volumes, and predicted tack welding time, the potential total yearly cycle time reduction for wear plate welding is up to 49,3 hours utilizing in-cell buffers. With two robots, the cycle time reduction will be 24,7 hours since the robot welding will be more starved over time due to the reduced cycle times than the tack welding times.

Considering the balance of robot welding and tack welding time can help decide how many in-cell buffers are optimal. Considering the estimated tacking times, the total tacking capacity needed is 744,30 hours per year. This can be compared to the computed robot welding capacity need depending on the number of robots. The ideal production capacity needed with one robot can be balanced with one in-cell buffer. But with two or more robots, up to three in-cell buffers can be considered without risking an imbalance between the total tacking welding time and the total robot welding time.

It should also be noted that the tacking times are highly theoretical, and the actual times will vary depending on the experience of the welding operator. Therefore it could be beneficial to dimension the robot cell so that the tacking times are the blocking factor. This is because theoretical tack welding times have more potential for time reductions than the theoretical robot welding times.

5.5.1.4 Loading of Wear Plates

The robotics concept can include different solutions for the loading of wear plates, as the following list of the feasible generated wear plate loading solutions reveals. The relative advantages and disadvantages of the solutions are summarized in Table F.4 in Appendix F.

- Overhead Crane Magnet
- Handling Robot Magnet
- Prepared Kit in Fixture/Jig
- Gantry Crane Magnet

If the tack welding of wear plates is supposed to be done in an in-cell buffer, it is essential that the loading of wear plates and tack welding does not interfere with the welding robot system. This will ensure the cell productivity and arc-on time factor. Also, to ensure the flexibility of the cell, the welding and assembly of wear plates should not be integrated. This allows for separate operation of the welding process and assembly process, offering higher adaptability to other products without the need for assembly and tack welding directly in the cell. Separated systems will allow minimizing the potential obstruction caused by a potential handling robot integrated, which is a must if the products are assembled and tack welded in a separate flow or station.

Since the location of the robot cell still is discussed internally at VCE, and as they are still preparing a proposition for a future factory layout, access to a suitable overhead crane cannot be guaranteed. Therefore, it is assumed that the production will be located in a new workshop without existing equipment or overhead cranes. This means that all investment costs have to be considered in evaluating wear plate loading.

Depending on what solution is chosen, different automation levels can be achieved. An overhead crane with a magnet attachment allows for manual loading and fixation of wear plates by the robot operator and welder. This means that the loading of wear plates and tack welding will be performed as in the current state. Utilizing a handling robot provides two different automation levels, either automated loading and placement of the wear plates and manual tack welding or automatic loading and placement of the wear plates and robotic tack welding. The first semi-automatic option induces a collaborative application, and the process must then be designed according to the safety regulations concerning collaborative robot applications. The latter would be the most efficient and safe option, but it requires robust and accurate sensors and calibration technology to be efficient. The last option also means that the tack welding operation would most likely not be needed. Instead, it would probably be beneficial to directly robot weld the joints as the technology allows. However, the productivity and arc-on time factor would be decreased since the welding robot would have to wait for the assembly and loading performed by a handling robot. This is since the different robot applications have to be coupled and integrated rather than not interfering with each other. Integrating the assembly and tack welding into the cycle, and a decrease in productivity, would require an investment in two sets of welding and handling robots to reach a similar output with non-integrated applications, which is why the Innovative concept in Appendix D treats both a single and double cell.

Due to the sheer size and considerable weight of the wear plates to be loaded, additional aspects have to be considered when evaluating the different options. Automating the handling and placement of wear plates induces complex problems that must be addressed.

1. The plate displacement due to gravity during lifting must be controlled and within a certain limit. Without some kind of control of the volume the wear plates are within, it will be impossible to program and guarantee collision-free robot trajectories.
2. The robot or gripper must adapt to bending variations in both the wear plate and the areas onto which the plates are placed on the body. This means that either the gripper or robot must be able to be adapted to the surface where the sheet is placed and push the plate for flushness.

The first problem is that the plate behaviour and sweep volume must be predictable to program efficient robot trajectories. Without control of the plate behaviour, flexing, and volume changes while moving the wear plate, unnecessary large safety distances must be considered while programming to avoid a collision. As seen in Figure 5.12, the total displacement for the largest and thinnest wear plate experience a pretty large displacement during lifting with only one magnet.

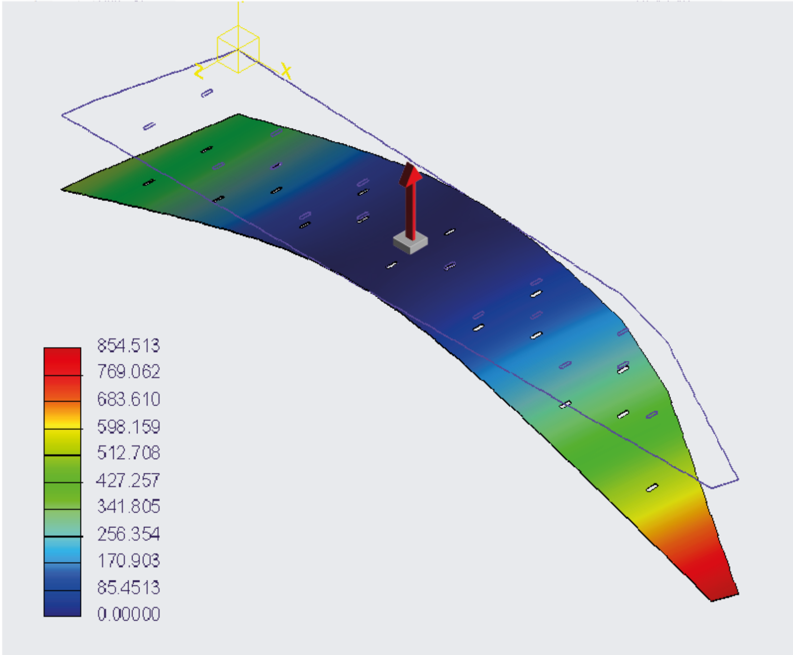


Figure 5.12: Large and thin wear plate static displacement in millimetres, with only one lifting magnet.

However, smaller and thicker plates, as seen in Figure 5.13, have very little to no displacement and would not require the same volume to be considered during programming. A smaller swept volume is desired since it gives more room in the cell to actually move and orient the wear plate.

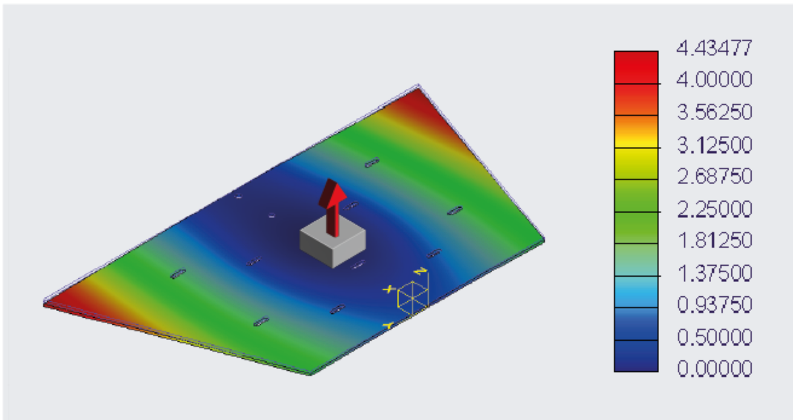


Figure 5.13: Small and thick wear plate static displacement in millimetres, with only one lifting magnet.

The flexing and lack of rigidness in a large suspended wear plate would mean that a large safety volume would have to be added around the wear plate to ensure collision-free paths during programming, as seen in Figure 5.14.

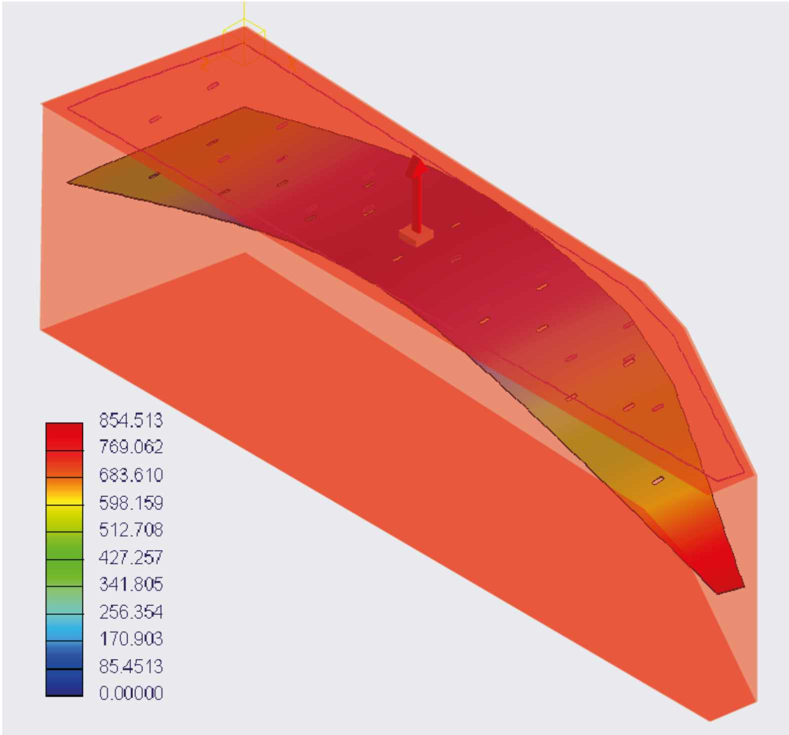


Figure 5.14: Volume to consider when calculating swept volume in robot movements, using only one magnet.

With more fixation points and magnets, a much smaller and manageable static and dynamic displacement can be achieved. For this, a gripper would have to be designed, as illustrated in Figure 5.15. A gripper would also make it easier to orient the part in space without the risk of dropping the wear plate or inducing high torsional forces. Due to the size and weight of the wear plates, additional mechanical security fixating the wear plate during transport and handling should be considered. According to Figure 5.16, the safety volume to be considered will also be significantly smaller, which is required for creating efficient collision-free paths.

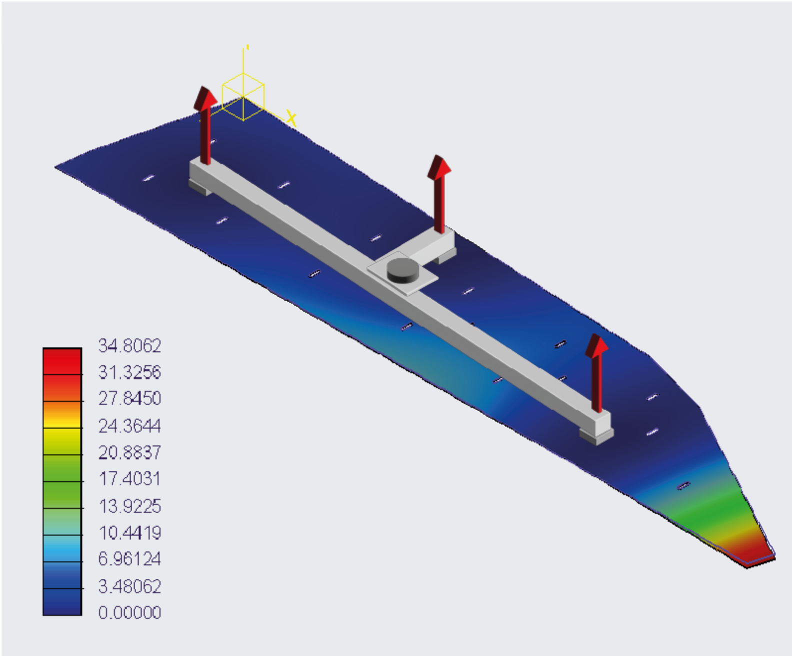


Figure 5.15: Small and thick wear plate static displacement in millimetres, with a three magnet gripper example.

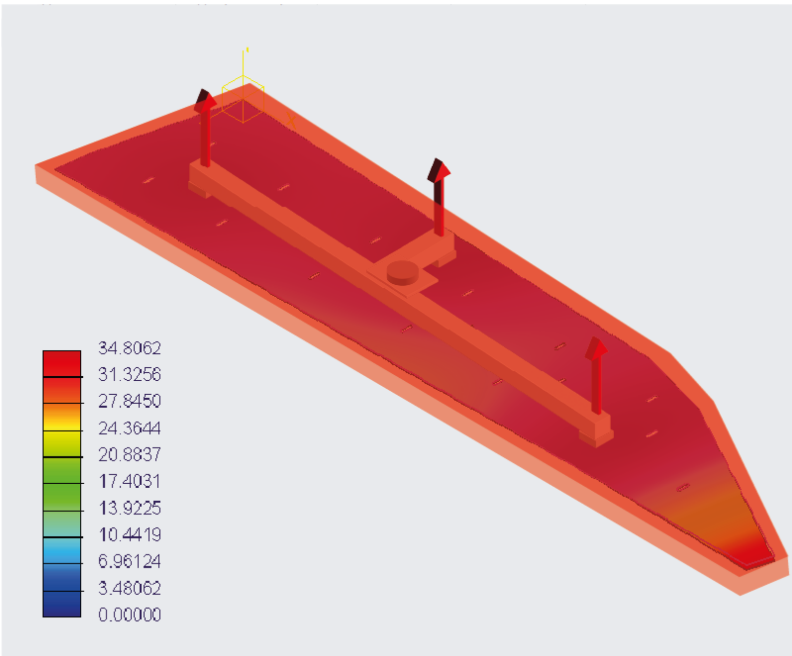


Figure 5.16: Volume to consider when calculating swept volume in robot movements, using three fixation points.

However, due to the variation in sheet size, several grippers would have to be designed to ensure the placement of wear plates in the body with restricted access. For instance, a gripper designed for large parts, a gripper designed for medium parts, and a gripper designed for smaller parts would be required. It is essential also to consider the adaptability of the different grippers so that all wear plates within a specific range can be positioned correctly in all positions in the hauler body without any clashes.

A redesign of the wear plates could also vastly simplify the automatizing possibilities of loading the wear plates. Larger wear plates could instead be divided into two or more smaller parts without any impact on the performance, reducing the large dimensions and weight required to handle. The potential displacement would also be less, and the gripper size could be more uniform. This idea is further presented in Section 5.5.1.8.

5.5.1.5 Fixation of Wear Plates

After loading a wear plate, it must be fixated or tack welded to the body to lock the geometry and secure its position. The robotics concept can include different solutions for the fixation of wear plates, as the following list of the feasible generated wear plate fixation solutions reveals. The relative advantages and disadvantages of the solutions are summarized in Table F.5 in Appendix F.

- Manual Tack Welding
- Robot Tack Welding
- Robot With Gripper

Manual Tack Welding refers to the application of manual tack welding and having welding operators fixate the wear plates one by one. This can be combined with any loading techniques but will require the welding operator to climb into the hauler body to weld the inside.

Robot Tack Welding refers to using the welding robot instead of letting humans weld. This induces high demands on the cell's adaptability and intelligence, an area that is currently not mature enough to support this application. This is an exciting area for the future, but a welding operator now excels a welding robot in this very varying environment. It can also be argued that if a robot can tack weld a wear plate, it might as well just weld the whole wear plate at once. However, the issue with this can be that the handling robot or loading and fixation device might interfere with the paths and induce reachability problems. Therefore, just fixing the wear plates one by one using a Robot With Gripper alternative would most likely be the case if the robot could weld the wear plates directly without any tack welding.

5.5.1.6 Calibration of Nominal Positions

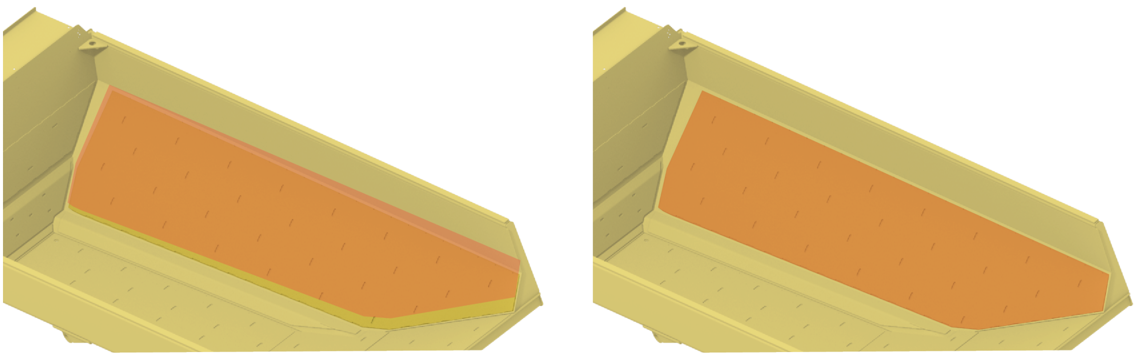
The robotics concept can include different solutions for the calibration of nominal position, as the following list of the feasible generated calibration solutions reveals. The relative advantages and disadvantages of the solutions are summarized in Table F.6 in Appendix F.

- Electrode Touch-Sense
- Gas Nozzle Touch-Sense
- Laser Proximity

- Laser Point Profiling
- Laser Line Profiling
- Laser Line Sweep Scans
- Structured Light
- 3D Laser Scanning

Calibration of nominal positions refers to both the calibration of the weld joint location or wear plate location, but also the body geometry on where to place the wear plate if automatic loading is included in the process. Important aspects to consider are how to collect the data and how to use and process the collected data. How to collect the data refers to a choice of sensor technology, and how to use the data refers to formulating a calibration method.

A robust and great calibration solution is an essential step in ensuring the robot arc weld gun starts the weld within the required tolerances, as Figure 5.17 exposes.



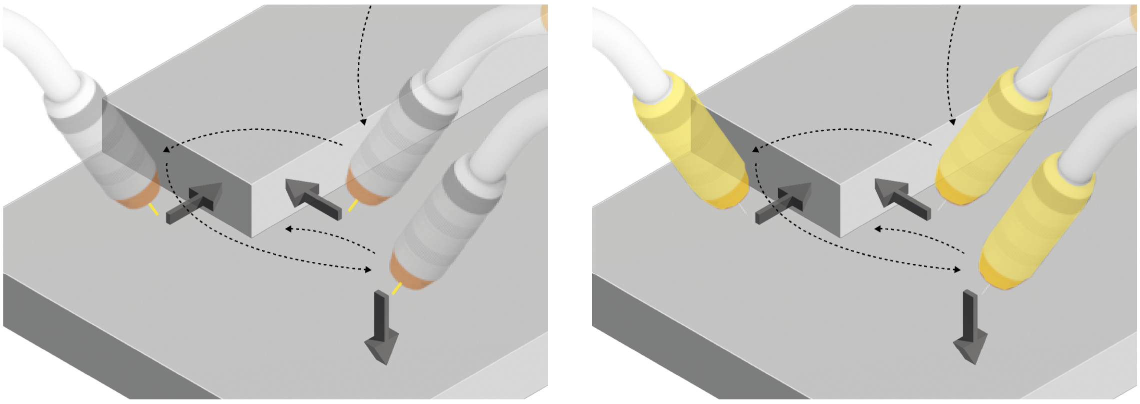
(a) (b)

Figure 5.17: Example of nominal wear plate position in red compared to the actual wear plate position, (a) before and (b) after calibration.

One rule of thumb is that a measurement system should contain as few sensors as possible due to cost and complexity. Another rule is that a measurement system should work within the smallest measuring range possible. Larger measuring areas result in poorer accuracy and resolution and poorer data quality.

The methods distinguish local and global calibration data and can each be applied to a respective set of different sensor technologies. In this section, the result concerning sensor technologies collecting local data will first be presented, followed by sensor technologies collecting global data. This also includes the description of two feasible main calibration methods, based on local and global data, for the different technologies.

As illustrated in Figure 5.18, Electrode and Gas Nozzle Touch-Sense sensor technology will provide an offset in position, comparing the actual data to the expected and nominal position. Nowadays, there are built-in commands and functions in the robot controllers and power supplies, facilitating the easy setup of search procedures and inducing low cost and complexity.



(a) (b)

Figure 5.18: Working principle for (a) electrode and (b) gas nozzle touch-sense start point search in this application, the part in contact highlighted in yellow.

Furthermore, a laser proximity sensor, as illustrated in Figure 5.19 use a point laser mounted on the welding torch to locate the surfaces. The technology is very similar to the touch-sense technology but will never be in contact with the workpiece.

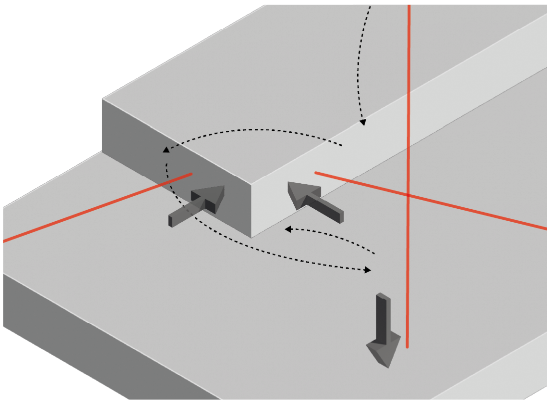
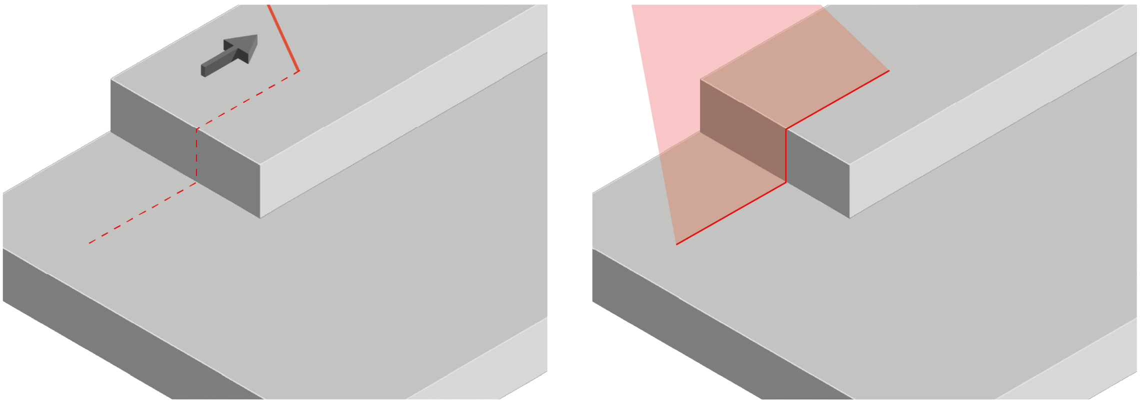


Figure 5.19: Triangulating start point using a laser proximity sensor.

A point and line laser mounted on the welding torch can be used to obtain a laser profile of a certain part of the workpiece, as illustrated in Figure 5.20. The point laser must be moved over the measurement area to obtain a profile, while a line laser can be statically placed above the measurement area.



(a) Laser Point Profiling (b) Laser Line Profiling

Figure 5.20: Working principles for obtaining a measurement profile using a laser, with (a) laser point profiling and (b) laser line profiling.

As illustrated in Figure 5.21, a line triangulation laser used for profiling can also be used as a scanning method. In this application, three different corners can be scanned, and the workpiece position can be calibrated with cloud-fitting. Depending on the field of view, measurement range and desired resolution, the frequency typically ranges from 500 to 10 000 Hz, which allows for rapid scanning of surfaces without losing resolution. The field-of-view (FOV) and measurement range typically range to 2000 mm respective 1500 mm, but a larger scan area has worse resolution and accuracy. The resolution typically ranges from 0,05 mm for smaller FOVs and ranges to 0,25 mm for larger ranges and FOVs. This limits the uses of the sensors since a set of sensors has to be mounted on a tool to cover and sweep the entire inside of the hauler body in one go. Otherwise, several sweeps are required to measure the whole body, which can be time-consuming.

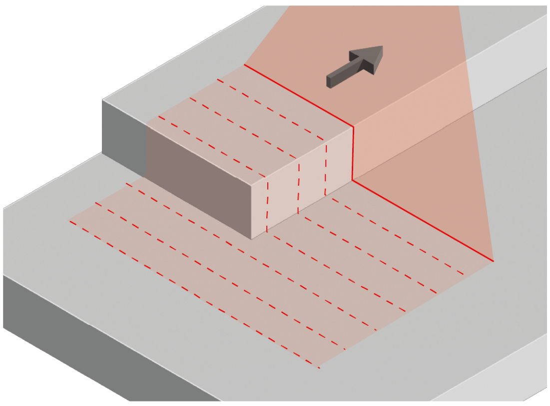


Figure 5.21: Sweeping scans using a line laser.

The sensor technologies mentioned above will suffice in calibrating a point in space, and the output will be either a position offset, 2D offset profile, or local point cloud. The sensor technologies collect only local data concerning a specific point. A specific point of interest is measured to calibrate a start point or workpiece. With this data, the system is limited in addressing the potential issues regarding a flexible robot application described in Section 2.3. But, the system will have enough data for real-time robot trajectory and process adaption, which is one of the issues that have to be addressed in a flexible robotics system discussed in Section 2.3. These methods can both be used to locate a single start point, and also by locating the three points required to locate and calibrate the position and orientation of a workpiece wear plate.

Current calibration at VCE consists of using touch sense or laser search to locate the start position of each weld joint. Due to the slit design and intermittent welding in the wear plate process, using the same approach would be very time consuming due to the many different weld seams required to find a start point, as illustrated in Figure 5.22.

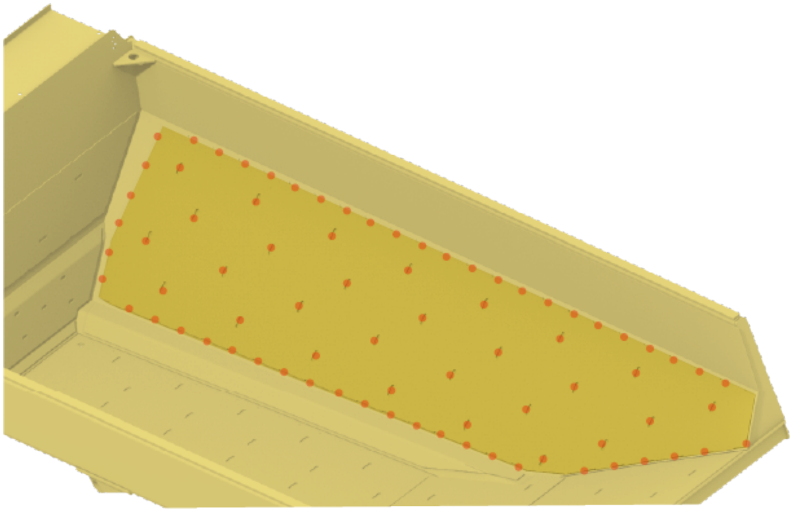


Figure 5.22: Individual start point searches are required for locating all welded joints separately for only one of the wear plates.

Due to the accuracy and repeatability of the laser cutting machine, each wear plate can be assumed to be nominal. Instead, only three measurement points would be required to triangulate and locate each wear plate in all 6 DOF, as illustrated in Figure 5.23. Calibrating the workpiece within a tolerance of ± 0.5 mm, and assuming the tolerance on the laser cut workpiece is ± 0.1 mm, all the weld joints related to the wear plate can also be considered to be calibrated sufficiently for arc welding.

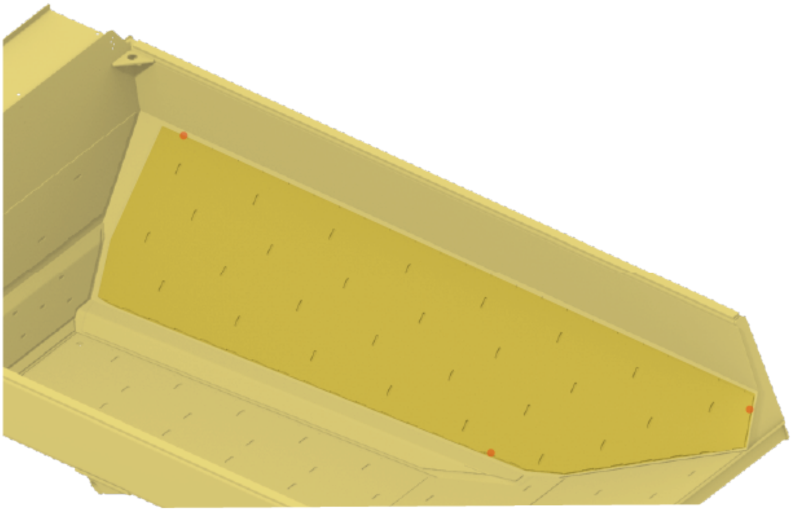


Figure 5.23: Individual start point searches are required for locating the workpiece position and orientation.

The local offset profiles obtained from the sensor technologies can be used to calibrate the nominal positions of the wear plates by first calculating the offset values for all points and then calculating a transformation matrix to apply to the wear plate coordinate system. A possible approach to this is illustrated in Figure 5.24

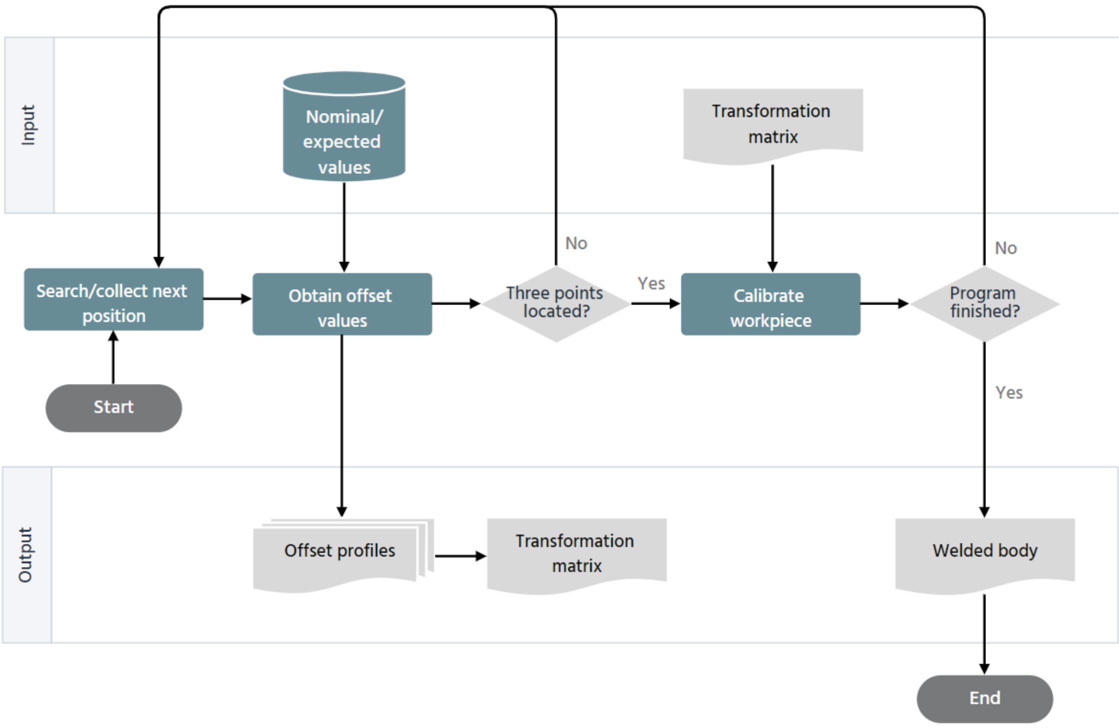


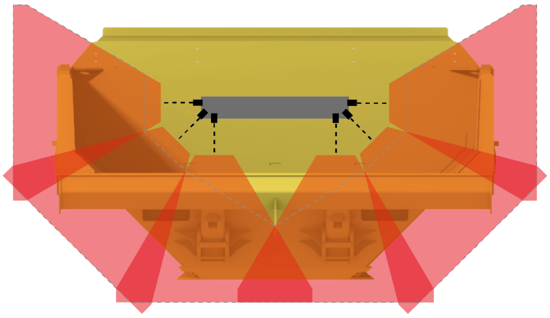
Figure 5.24: Flowchart for the process of calibrating using Electrode Touch-Sense, Gas Nozzle Touch-Sense, Laser Proximity Sensor, Laser Point Profiling and Laser Line Profiling.

All the screened and feasible solutions in this report rely on calibrating each wear plate independently as a workpiece, utilizing the low variation of the laser cut parts. But, the potential sensor technologies and calibration methods slightly vary, with different complexity, cost, accuracy, and robustness.

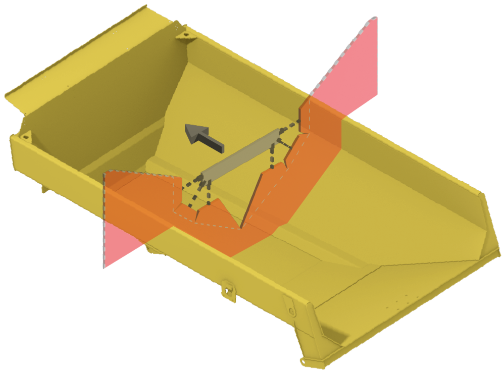
However, with more advanced sensors and calibration technology, it is possible to achieve a higher degree of automation and a truly flexible and adaptive robot welding application. A laser line, structured light, or laser scanner can provide a complete and global point cloud of the real-world workpiece. This will help in addressing additional potential issues described in Section 2.3. The point cloud and the sensors generating it facilitate the connection between a real-world model and a nominal CAD world model, ultimately supporting real-time calibration of the workpiece positions via cloud fitting. Furthermore, the cloud point data enables the robot system to respond to environmental changes in real-time by activating alternative actions or trajectories if an obstacle blocks the nominal trajectory. The more detailed data will support the prediction of the robustness of a flexible robot welding process and the automatically proposed adaptions, facilitating autonomous decision-making in the robot welding process.

Global measurements and scans of the complete hauler body can come with several benefits and induce longer cycle times and higher costs. Local measurements will only take a few seconds each, and depending on the number of wear plates to be calibrated, the impact on the cycle times varies. Assuming a general local search time of 4 seconds per point and 9 points required per workpiece, the total measurement and calibration time per cycle will range from 2 to 4 minutes, which is very little compared to the total cycle time. But, with a complete global sweeping scan of a product, as described below, a scan time of 3 to 5 minutes per welding position can be expected, which equals a total measurement and calibration time of 15 to 25 minutes per cycle. Another essential aspect when scanning large objects with a robot is that the robot's accuracy can affect the scan data. If the scanner has no external reference, you are entirely dependent on the robot's repeatability and positioning accuracy. This can also vary over time and worsen the more the robot wears. For increased accuracy, an external reference must be added. This is especially important in meteorological applications. In this project and application, due to the large products and the fact that the scan data will primarily be used to calibrate the workpiece in a robot application, the robot's repeatability and positioning accuracy will enable using the robot as a reference.

Utilizing several line lasers, a measurement range covering the complete hauler body can be created, generating a global data set. This can be achieved by mounting several line lasers on a tool mounted on a robot, as illustrated in Figure 5.25. However, due to the expensive unit price of the sensors, such a solution would not be very cost-effective and only save a small amount of time relative to the cycle times. Furthermore, the calibration process of the lasers themselves will be more complex. The risk of the lasers being wrongly calibrated increases, ultimately increasing the risk of one of the lasers being incorrectly calibrated and measuring incorrectly.



(a)



(b)

Figure 5.25: Sweeping scan using several line lasers.

As illustrated in Figure 5.26, structured light scanning requires many snapshots to be stitched together, either by using an absolute reference in the world coordinate system or using the robot position as a reference. The many scans required to obtain a complete point cloud of the product makes this method time-consuming, but the number of data points would be significant. A structured light scanner can also be used only to take snapshots of points of interest. For instance, the area surrounding a weld start point to calibrate only the position of the specific start point.

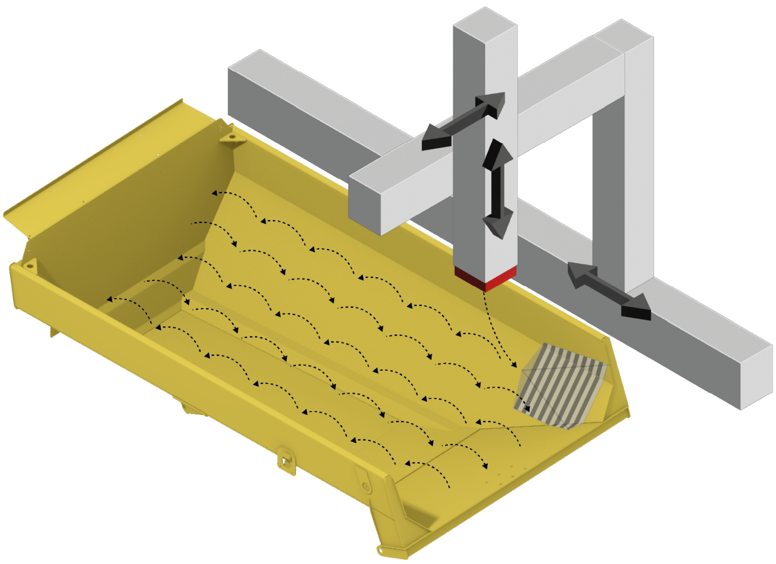


Figure 5.26: Structured light 3D scanning.

To decrease the scan times which can be experienced by a sweeping laser or structured light scanner, a rotating stationary 3D laser scanner mounted on the gantry can be utilized, as illustrated in Figure 5.27. This will allow for a complete snapshot of the complete product within a few minutes while also providing sufficient accuracy and resolution. A Surphaser 100SR or similar would be an excellent choice for this application, providing a recommended scan range of 1 to 7 m and a range uncertainty of <0.3 mm at 3 meters

(Surphaser, 2022). However, the cost and implementation of such a solution would be much greater than the previously mentioned technologies.

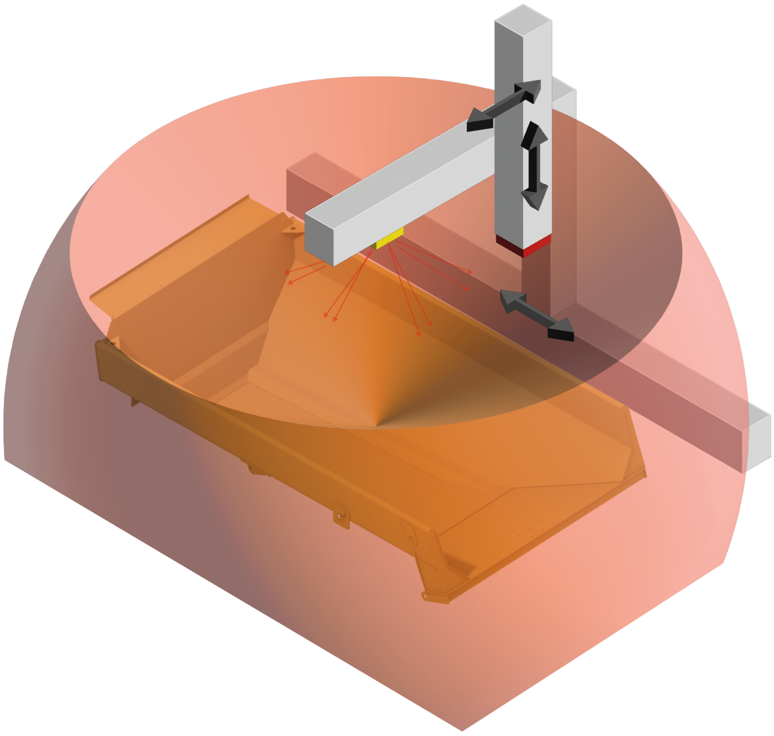


Figure 5.27: Laser 3D scanning with a scanner mounted on a gantry.

Furthermore, more extensive data in the form of point clouds and similar could be used for the purpose of tracing the quality and process variations. A lot of data would be generated supporting variation and tolerance analyses in the hauler body production flow beyond the operational calibration usage.

Figure 5.28 illustrates a recommended procedure for calibrating using global point cloud data collected by laser line sweeps scans, structured light, or laser scanning. Software solutions such as Polyworks can first identify the product by comparing relevant geometries and then automatically fit the point cloud to a CAD model, a process illustrated in Figure 5.29. This will generate a deviation profile which can be used to transform the coordinate systems or frames for the robot trajectories and wear plates.

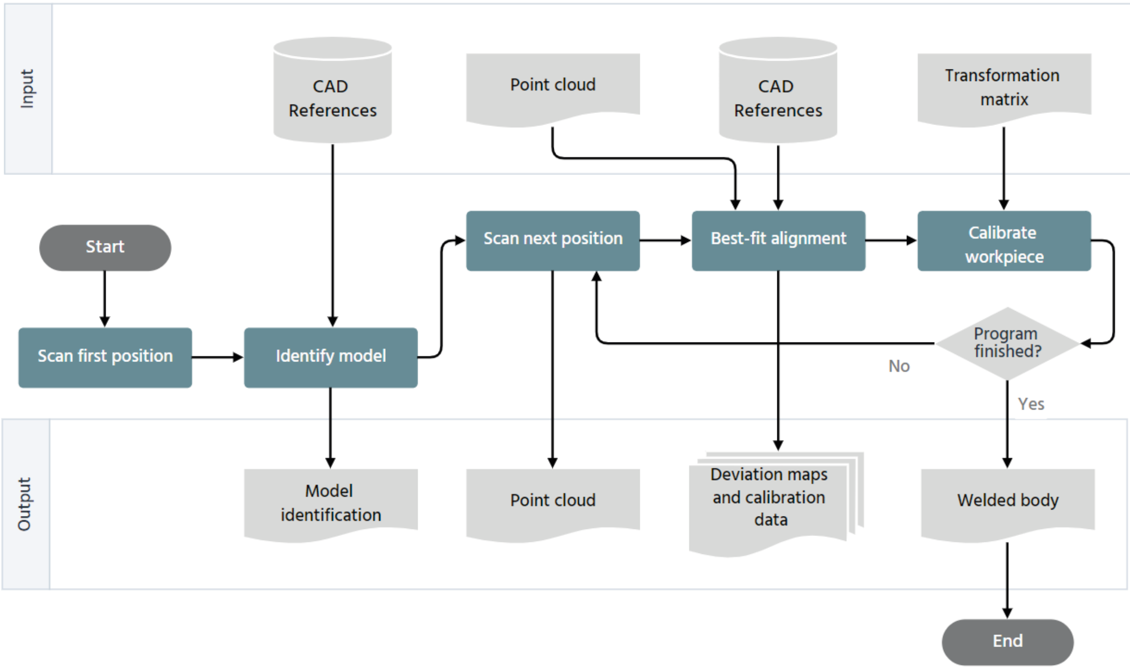


Figure 5.28: Flowchart for the process of calibrating using Laser Line Sweep Scans, Structured Light, and 3D Laser Scanning.

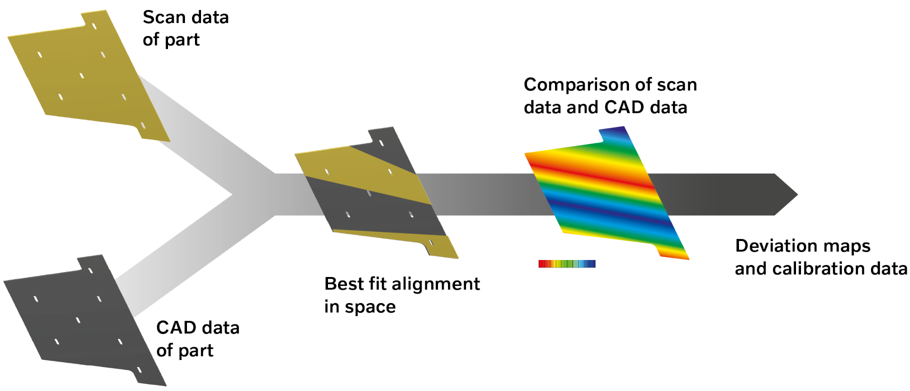


Figure 5.29: The process of best-fit alignment using cloud fitting.

This shows that structured light and 3D laser scanner technology is the only correct choice in achieving a truly flexible robotic system rather than a pseudo-flexible system.

5.5.1.7 Seam Tracking

The robotics concept can include different solutions for seam tracking, as the following list of the feasible generated seam tracking solutions reveals. The relative advantages and disadvantages of the solutions are summarized in Appendix F.7 in Appendix F.

- Through-Arc
- Laser
- Vision Camera

- Digital Twin

Seam tracking is an important technology and aspect to consider to secure the quality output and flexibility of the cell. Seam tracking technology will address one of the potential issues essential to consider when implementing flexible robot systems, as described in Section 2.3.

Further aspects such as weld quality monitoring could also be considered in the choice of seam tracking technology.

5.5.1.8 Wear Plate Design Changes

The robotics concept can include different solutions concerning the wear plate design, as the following list of the feasible generated design solutions reveals. The design solutions can enable a higher degree of automation or improve productivity and should be considered before implementing a robotic solution. The relative advantages and disadvantages of the solutions are summarized in Table F.8 in Appendix F.

- Enlarge Slots
- Offset All Walls
- Offset Intermittent Walls
- Modify Welding Angles
- Reduce Wear Plate Sizes
- Round Sharp Corners
- Self-Locating Parts
- Flat Bar Redesign

One of the redesigns proposed before this project was to update the slot design on the wear plates, as illustrated in Figure 5.30. It was said that this would enable the automatizing of the wear plate welding since the number of slots to be welded would be greatly reduced. This would mean that the robot would weld fewer but longer slots, which would be advantageous. There would also be a lot less time to weld a wear plate since there would be less time to search for start points.

However, the results of this project have shown the opposite. The time for welding a wear plate with the enlarged slots would be about three times longer than welding a wear plate with the current slot design, according to the time computations, including the search times presented in Table 5.7. This is because a lot more material is put down when welding the long slots. Furthermore, welding tests performed within this project have shown no issues in welding the current slot design with a robot in one go, which diminishes the primary need for a slot redesign.

(a) (b)

Figure 5.30: Example of the proposed slot resdesign, with (a) current design and (b) new design.

Table 5.7: Comparison of computed cycle time with weld, search, and via times, for a representative model.

Slot Design Welding	Time
Current	17,03 min
New	51,95 min

Another aspect which could be affected by an updated slot redesign would be the rigidity of the wear plates, where larger slots would decrease the rigidity, as demonstrated in Figure 5.31. This could be beneficial in ensuring flushness between the hauler body and wear plates when loading them. But, at the same time, it could be disadvantageous since the design will increase the internal stress in some areas when lifting the wear plates. Comparing the current design with the new one in the static load case previously presented, where the wear plate is suspended in the air with one magnet, it is noted that the maximum displacement has increased by 17%, from 854 mm to 1003 mm. This means that the rigidity of the wear plate can be decreased. But, on the other hand, the internal stress levels have been increased due to reduced stiffness. But, the stress levels do not go beyond the yield strength of Hardox 450, meaning the redesign is not impossible, but extra care should be put into validating the design feasibility due to the increased stress levels.

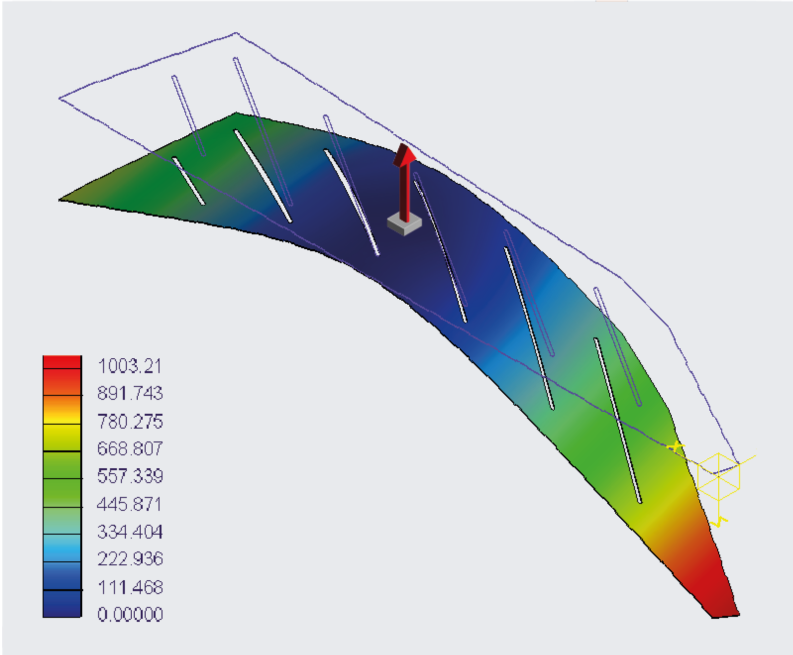


Figure 5.31: Wear plate static displacement with the new design (mm).

The only benefit of updating the wear plate design would be less rigidity and the need for less weight pressing down the wear plate during tack welding. However, the reduction in the weight needed to ensure flushness would at maximum be 50%, meaning that a weight of 500 kg pressing down on the wear plate would still be necessary.

Another issue identified was the reachability of the welding seams with the welding torch. The wear plate is currently not designed for automation. The current design induces some reachability problems and clashes if the joint is welded using the optimal welding angles and parameters. The reachability and clash issues concern about 50% of the welding joints in wear plate welding. For all fillet joints, a 45° welding angle is desired to obtain during welding to ensure the penetration and quality of the weldment. But, the wear plate design does not allow this angle without inducing clashes and reachability issues.

This can be solved in three different ways; Offset All Walls, Offset Intermittent Walls, and Modify Welding Angle. Offset All Walls refer to reducing the overall size of the wear plate. Offset Intermittent Walls reduce the wear place size only where the intermittent weld slot is present, keeping the overall plate size. Offsetting only the intermittent walls will keep as much abrasion protection as possible while still enabling the robot to reach all seams. These two redesign approaches is illustrated in Figure 5.32

(a)

(b)

Figure 5.32: Two wear plate redesign approaches to improve reachability for hard-to-reach seams are overlaid on a section of a current wear plate design. With (a) offset all walls to reduce overall size, and (b) offset intermittent walls to reduce only slots.

Modify Welding Angles refers to welding the wear plates with a higher welding angle than normally recommended, which is possible only due to the lack of requirements on the penetration of the weld. Welding tests with a robot have been performed within this project, and a 65-degree welding angle has been verified to provide adequate weld quality. A larger welding angle than that will have a negative impact on the welding quality and is not recommended in the welding of wear plates.

According to this project's initial reachability and clash analysis, the required offset and reduction of sidewall dimensions ranges from 0 to 80 mm depending on the specific wear plate and its position. Furthermore, keeping the current design the required welding angle ranges from 45° to 76° to ensure a collision-free welding path. The approaches to redesign the wear plates previously mentioned can be combined with an increased welding angle to ensure reachability and no clashes. This means the welding angle can be increased up to 65° and the sidewall dimensions be slightly reduced where necessary. It shall be noted that these ranges and values do not consider any approach, departure, or variation of the weld torch position and only consider the required offset and angle for a nominal clash-free weld. An additional offset depending on the weld trajectory context should be added to ensure a safe approach, safe welding, and a safe departure.

An additional design change which could be imposed is the size reduction of the wear plates, as depicted in Figure 5.33. This is required to handle the weight and dimensions of the largest wear plates with a robot. They can be redesigned to have minimal impact on wear and abrasion protection. However, it is only recommended to do this redesign if necessary since it will add more work both to redesign the wear plates and add cycle time due to more welds required with the new design.

Figure 5.33: Example of how the wear plates can be divided into several plates to reduce the separate plate weight and enable a higher degree of automation.

Additionally, possible design changes which should be considered are the rounding of sharp corners to enable a continuous weld over corners, design features that will allow self-locating of the wear plates, and a flat bar redesign with a width specific for each body size. All these changes will increase productivity. The potential cycle time reduction savings with a flat bar redesign range between 14 and 28 minutes per product, based on the fact that up to two or three weld layers are required to meet the quality requirements on some models.

5.5.1.9 Weld Torch Setup

The robotics concept can include different solutions for the weld torch setup, as the following list of the feasible generated weld torch setup solutions reveals. The relative advantages and disadvantages of the solutions are summarized in Table F.9 in Appendix F.

- 1 Single
- 2 Single
- 1 Twin
- 1 Single & 1 Twin
- 2 Single & 1 Twin

Due to the flexibility of the robot application, different setups of weld torches have to be considered to cover all different needs for different models and products. Different welding torch necks can be used depending on the desired duty cycle. As illustrated in Figure 5.34 (a) and (b), the neck size will vary depending on the rating, and lower ratings allow for a thinner gas nozzle and higher reachability. Therefore, it could be advantageous to utilize several different welding torches and a torch change station. This means using a lower-rated single torch with a smaller gas nozzle in applications not requiring high duty cycles increases the reachability and flexibility for weldments with lower quality requirements. The smaller nozzle size will enable one to reach in tighter spaces and weld with a higher welding angle. A higher rated single welding torch can be used for weldments with a higher duty cycle. And, a twin welding torch can be used for weldments where a twin setup is advantageous, with longer joints with good reachability and no obstacles.

(a) (b) (c)

Figure 5.34: Different welding torches, (a) single with lower rating, (b) single with higher rating, and (c) twin.

5.5.1.10 Program Weld Location & Parameters

The robotics concept can include different solutions for the programming of weld locations & parameters, as the following list of the feasible generated programming solutions reveals. The relative advantages and disadvantages of the solutions are summarized in Table F.10 in Appendix F.

- Manual
- Import CAD Data
- Auto-Detect

Manual refers to manually programming the weld trajectories using offline programming software such as Delfoi ARC. Manual offline programming is a time-consuming process, even though today's offline programming software offers great support for quicker programming. Offline programming performed manually, or semi-automatic with support from the software is considered to be object-level programming.

Import CAD Data refers to utilizing model-based welding definitions to generate paths automatically. It relies on an extensive and continuously updated database of workpiece models containing definitions connected to the 3D model. Thus, it is possible to extract the desired weld path position and orientation and pass through parameters describing the operation. There are currently standards like XMCF (ISO/AWI PAS 8329, 2022) under development to describe joints, and Creo Parametric already have great support in exporting model-based welding definitions in machine-readable XML format. Software like Delfoi or Industrial Path Solutions (IPS) can import the XML data to perform curve generation and planning automatically. IPS can visualize the alternatives and replan or edit the curves before optimizing the sequences and exporting robot code. However, the method of utilizing model-based definitions can imply a large initial workload on the mechanical engineering department if the definitions are currently not model-based. But in the long run, the time from design to production will be significantly reduced. This approach can be considered to be process-level programming.

Auto-Detect refers to using machine learning or neural networks to detect weld paths automatically. This approach is commonly used where workpiece models are not available, and 3D scans of the workpiece are instead processed. Auto-Detect can also be used on model assemblies of a workpiece. This technology supporting this method is still not robust enough to include in a fully automatic process. It will provide decision support and require input from human operators to verify that the detected weld paths correspond to the desired weld locations. This approach can be considered to be the goal-level programming.

5.5.1.11 Plan & Optimize Weld Paths

The robotics concept can include different solutions for the planning and optimization of weld paths, as the following list of the feasible generated optimization solutions reveals. The relative advantages and disadvantages of the solutions are summarized in Table F.11 in Appendix F.

- Manual
- Auto-Solve
- Reinforcement Learning

Manual optimization refers to manually optimizing and planning the weld paths using offline programming software and human intuition and experience. However, human intuition has strict limitations, and the optimal solutions may never be found. The process of manually balancing is also rather time-consuming.

Auto-Solve refers to using computational tools or machine learning to find an optimal solution for load balancing and sequencing automatically. Software like IPS excels in path planning and sequencing using probabilistic roadmap planners (Bohlin, 1999). IPS has a proven effect of 25% cycle time reduction and 75% reduction in time spent on commissioning and production preparation (Industrial Path Solutions, 2022). IPS provides deterministic solutions in weld operation distribution among the robots and planning the paths between the operations. Optimization and minimization of the robot to robot conflicts and coordination losses are also automatically solved before exporting robot code and synchronization signals. Generating a robot program similar to those for wear plate welding would require between 30 to 60 minutes of computation time.

Reinforcement learning refers to using artificial intelligence to autonomously plan the robots' motions. This is an area where a lot of research is conducted, and therefore the technology is not mature enough to be implemented in production. NVIDIA Isaac Sim is one example of a tool and simulation software providing a virtual environment to develop, test, and manage AI-based robots (NVIDIA Developer, 2022).

5.5.2 Robotics Selection

The full results of the robotics selection process are presented in Appendix G.

Table 5.8: Robotics evaluation matrix scores

Concept	Score	Relative Score
Low Tech	72	74%
Medium Tech	97	100%
High Tech	86	89%
Innovative	86	89%

Since the weighing of the criteria varies over time, and with new technology uprising, the remaining concepts should not be excluded. Based on the evaluation, the Medium Tech concept is the concept most beneficial to implement, considering the aspects and criteria mentioned in Section 4.4.1, since it received the highest relative score in the evaluation matrix.

Therefore, the Medium Tech concept is concept chosen to be further developed and modelled. The concept will be further combined with the outcome of the workpiece positioner concept study to form an overall production concept.

5.5.3 Workpiece Positioner Evaluation

Of the 40 generated and combined concepts, only 22 concepts passed the elimination matrix. The complete elimination matrix is presented in Appendix H.

In the first Pugh matrix, the concepts scored between minus six and six in the first Pugh matrix. The complete first Pugh matrix is presented in Appendix I. In the second Pugh matrix, the concepts scored between minus six and two. The second Pugh matrix is presented in Appendix J. Ten concepts passed from the two Pugh matrices and were brought into the Kesselring matrix. The results from the Kesselring matrix screening are summarised in Table 5.9. The full Kesselring matrix is displayed in Appendix K.

Table 5.9: The result from the Kesselring matrix.

Concept	Score in points	Score in %	Rank
Concept 1	196	89	5
Concept 8	197	90	4
Concept 13	174	79	9
Concept 14	174	79	9
Concept 15	175	80	8
Concept 25	181	82	7
Concept 32	209	95	1
Concept 37	183	83	8
Concept 39	202	92	2
Concept 40	201	91	3

The five best concepts chosen for further analysis is Concept 1, 8, 32, 39, and 40 marked with green in Table 5.9. The further analysis of the concepts from the Kesselring matrix is presented in the following sections.

5.5.3.1 Loading and Unloading Comparison

A comparison between the relative advantages and disadvantages of rail, AGV and overhead cranes as loading and unloading assistance is presented in this chapter. A table that summarises the following relative advantages and disadvantages is presented in Appendix L.

Rail is cheap to buy and a robust alternative that solves the loading and unloading transportation, but it has its flaws when considering possible future changes to the production layout. Changes to the rail will come with large investment costs and possibly interruptions to the production. Changes to the factory layout frequently occur when new products are released, or old products are removed, making it an advantage if it is easy to make changes to the material transport system. Since changes will occur, the long lifespan of rails might also be too long since they most likely will be moved or removed before it has been worn out.

An AGV is very flexible and can easily be reprogrammed to new routes if needed. It can transport itself almost anywhere and is capable of handling large weights. The downside is that it has to be charged and is expensive to invest in. The charging should however not be a problem since the robot welding cycle times are long, and the AGV will have time to charge during the welding. Compared to the rail, the cost of an AGV might also be better than expected since it does not require any extra cost when changing its routes. This possibly makes it an equally economic option as the rail in the long term depending on how often the rails are changed.

An overhead crane provides good lifting possibilities, and there is a lot of experience in using overhead cranes within the company. However, lifting the body in the air is not required, and the roof and beams in the facility are not designed to carry an overhead crane designed to lift 20 tons. The overhead crane is also not designed for longer transports, and a second transportation method is therefore needed as a compliment.

Considering all of this, it is clear that AGV is the best solution regarding the current needs and future flexibility. The extra investment cost that it comes with is worth it when comparing it to the downsides of the other options.

Based on this additional comparison, Concept 1 can be eliminated since it contains a rail. Concept 39 was generated in the third iteration of the concept generation stage as an improvement of Concept 1, further motivating the elimination of Concept 1. The same goes for Concept 8, which also can be eliminated since Concept 40 was created as an improvement of Concept 8.

Concept 32 and Concept 40 are identical with the only difference in the used suspension subsolution. Concept 32 utilizes locking pins, and Concept 40 utilizes a bolted adapter, for connecting the body to the positioner during loading and unloading. A bolted adapter would have to be mounted on the body before loading the positioner and locking pins are therefore seen as the better alternative. Due to this, Concept 40 is eliminated and the two concepts for further evaluation are Concept 32 and Concept 39.

5.5.3.2 Displacement Feasibility

Since Concept 32 is only mounted and suspended in the front, tests were done to see whether the bodies could withstand the induced displacement and stress. An initial calculation, according to the equations in Section 4.3.2, showed that the stress induced on the mounting should not exceed 312,5 MPa.

The material currently used (Hardox 450) for producing the bodies has a yield strength of 1250 MPa SSAB (2022). This makes it entirely possible to design a suspension system integrated or welded onto the body that can handle the applied forces. Therefore, the concept was further evaluated and analysed.

An internal study at VCE initiated within this project was also conducted to find the most optimal fixation points on the body concerning stress levels. The results were used for the design of a one-sided suspension system. The used fixation points is illustrated in Figure 5.35.

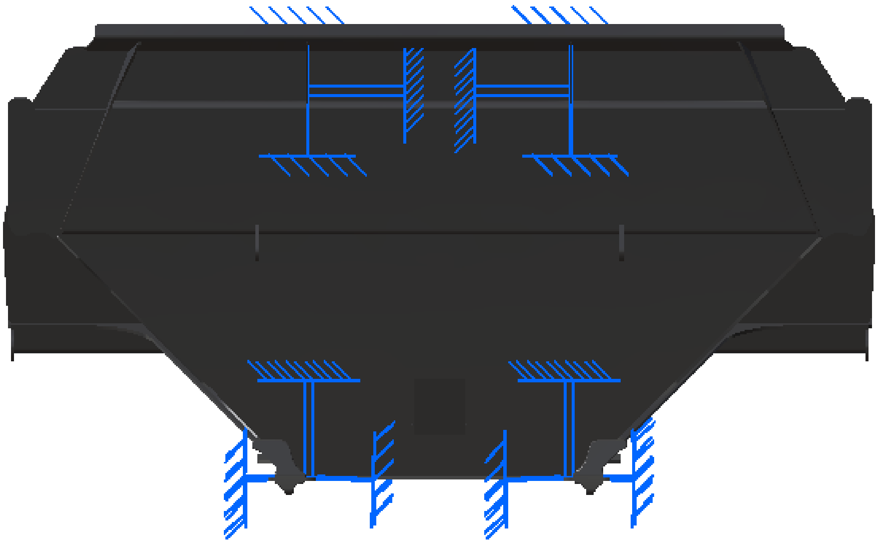


Figure 5.35: Optimal fixation points used in the study.

Based on a further FEM analysis, the maximum displacement and Von Mises stress identified for each body in three different welding positions when mounted to one end are displayed in Table 5.10.

Table 5.10: FEM results are summarized for different selected cases.

Body	Roll	Pitch	Max Displacement	Max Von Mises Stress
AH6	0 °	0 °	20,4 mm	703 MPa
AH6	90 °	0 °	7,99 mm	272 MPa
AH6	45 °	20 °	18,8 mm	537 MPa
AH2	0 °	0 °	15,2 mm	512 MPa
AH2	90 °	0 °	7,12 mm	332 MPa
AH2	45 °	20 °	14,4 mm	550 MPa

The maximum Von Mises stress from the table is 703 MPa, which occurs when the AH6 body is held upright with no roll or pitch. This stress is no issue due to the margin to the Hardox 450 maximum yield strength of 1250 MPa for a 20 mm thick plate (SSAB, 2022). Based on this, the deformation should only be elastic, and the body will return to its original geometry after being unloaded from the positioner. However, a higher safety factor could be desired in ensuring the safety of the system and lifting on only one side of the body.

The maximum displacement is 20,4 mm and occurs at the chute of the AH6 body with no roll or pitch. A large displacement could pose a problem when wear plates are welded since they would be welded on a temporary deformed surface. This could cause the wear plate welds to break or crack when the hauler body returns to its natural geometry, or completely prevent the body from returning to its original geometry. When studying the displacement further, it is evident, according to Figure 5.36, that the displacement is linear with the bottom plate. Therefore, the displacement is not a problem for the wear plate welding since the shape of the surface the wear plates are welded onto is linear throughout the process. The only parameter changing during the displacement is the angle between the bottom plate and the front.

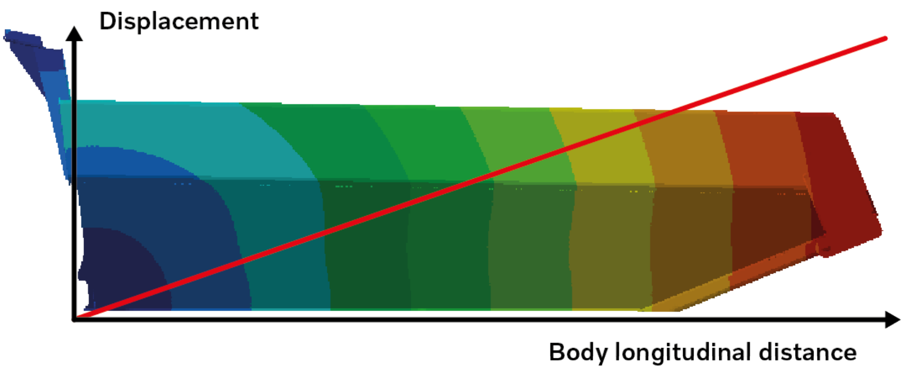


Figure 5.36: Linear displacement when suspended in only front.

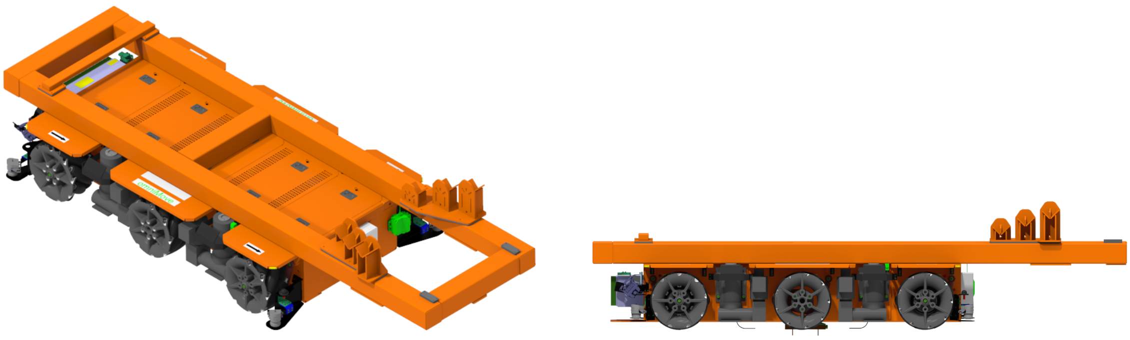
Discussions have also been held with multiple suppliers of positioners to ensure that it is feasible to dimension a positioner that is capable of handling these weights and torques, and that it is possible to invest in such a positioner for a reasonable price.

5.5.4 Workpiece Positioner Prototyping

This section presents digital prototypes of the final concepts from the evaluation stage. A possible AGV solution for transporting, loading and unloading the bodies in the positioner is also presented, together with a fixture for transporting the body on the AGV.

5.5.4.1 AGV Solution

For transportation, loading and unloading of the bodies, an AGV is recommended in the two final concepts. One feasible AGV capable of handling the process requirements of the application is the 12 tons KUKA Omnimove, illustrated in Figure 5.37. It can transport all current bodies, and for future bigger and heavier bodies it can be linked with another 12 tons KUKA Omnimove for 24 tons transport capacity. The two AGVs could then work separately or alone, depending on the needs. This would make it possible to transport heavier bodies and prepare for increased production volumes. The AGVs could also be used in other parts of the factory for transporting material or other products.



(a) **(b)**

Figure 5.37: The recommended AGV, a 12 tons KUKA Omnimove, with the integrated fixture.

A fixture for transporting the body has been integrated to guarantee that the bodies do not move on the AGV when being transported. The fixture supports the body as visualised in Figure 5.38.

(a) (b)

Figure 5.38: A hauler body loaded onto the fixture and AGV.

5.5.4.2 Concept 32

The concept consists of a headstock with three degrees of freedom; heave, pitch and roll. The heave and roll motions are performed by lifting or rotating the plate to which the workpiece is attached. The workpiece can then be pitched by tilting the plate positively or negatively.

Because of the vast dimensions of the bodies and the high pricing of the headstock, a tailstock will be required for products heavier than 10 tons or longer than 7 meters. The tailstock can be used as a secondary attachment point where the workpiece rests and follows the movements made from the headstock. The tailstock has two degrees of freedom, heave and surge. Heave is required to be able to pitch workpieces attached to both the head and tailstock. The cradle to which the workpiece is attached to the tailstock can move up and down along the tailstock frame causing the necessary movement for pitching. Since the headstock is used together with the tailstock in a system context, synchronization needs to be implemented to allow the head and tailstock to work seamlessly.

Surge is needed to fit workpieces of different lengths between the head and tailstock. The tailstock is placed on rails and can therefore easily be moved closer or further away from the headstock, depending on the size of the workpiece.

Since the headstock sometimes is used as the only gripping point, it requires a firm anchoring to the floor. This will require a strong foundation in the floor under the headstock to secure it properly. The final positioner concept is presented in Figure 5.39.

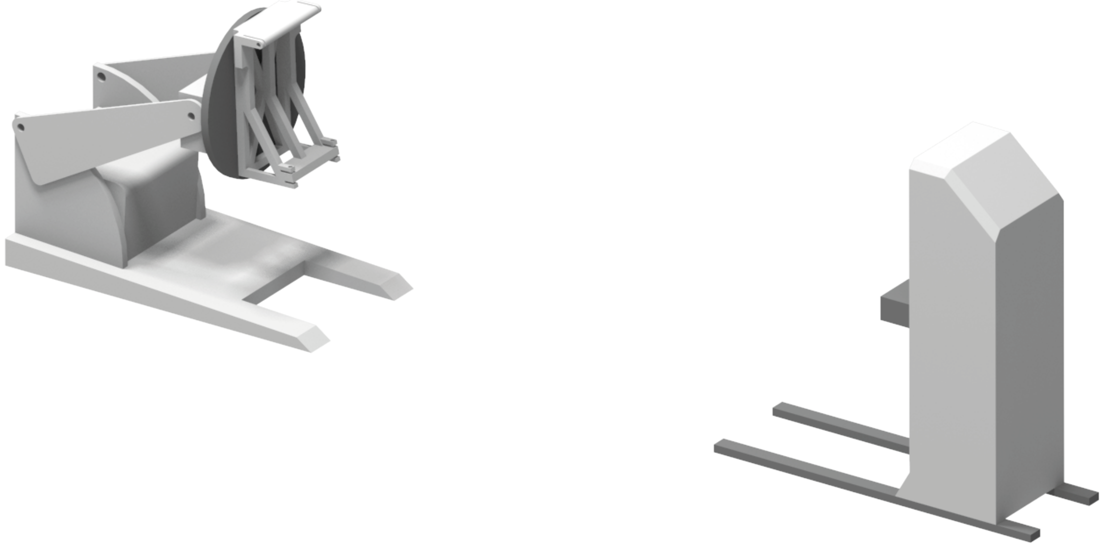


Figure 5.39: Overview of the positioner.

A positioner like this simplifies the attachment procedure of the workpiece since it is mostly only attached to one end. It could also help when designing future products since attachment is only necessary on one side of the workpiece, although the workpieces need to be designed to withstand their self-weight. This type of positioner would also make it possible to pitch the body and align it with the floor. The alignment makes it more ergonomic for workers to manually load the wear plate since they do not have to climb up into the body but can instead simply walk into it. This position is illustrated in Figure 5.40.

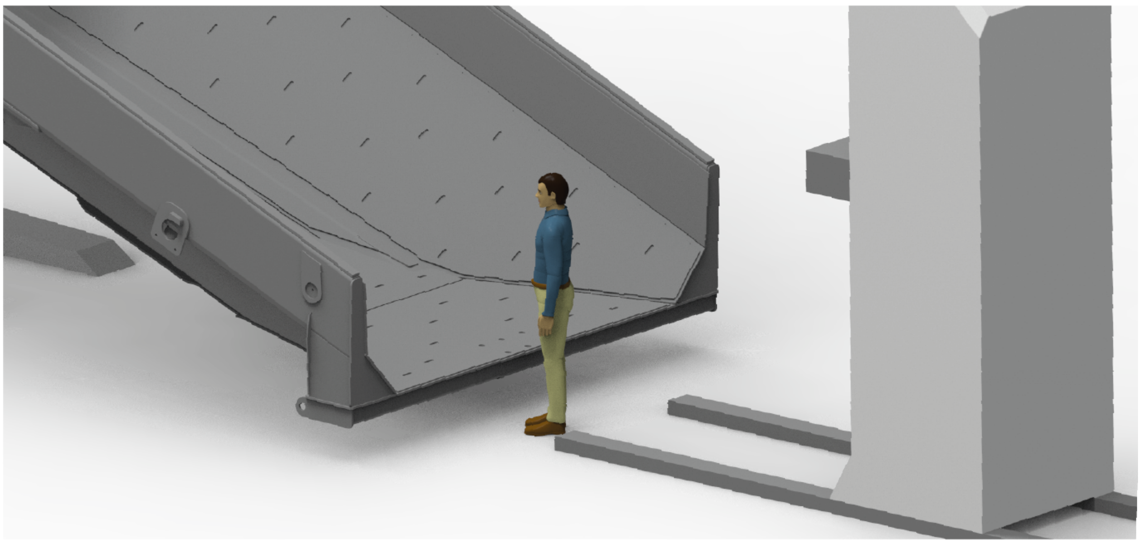


Figure 5.40: The capability of climbing into the body safely and ergonomically.

The minimum tilt requirement according to the requirement specification list is 20°. Figure 5.41 illustrates this position.

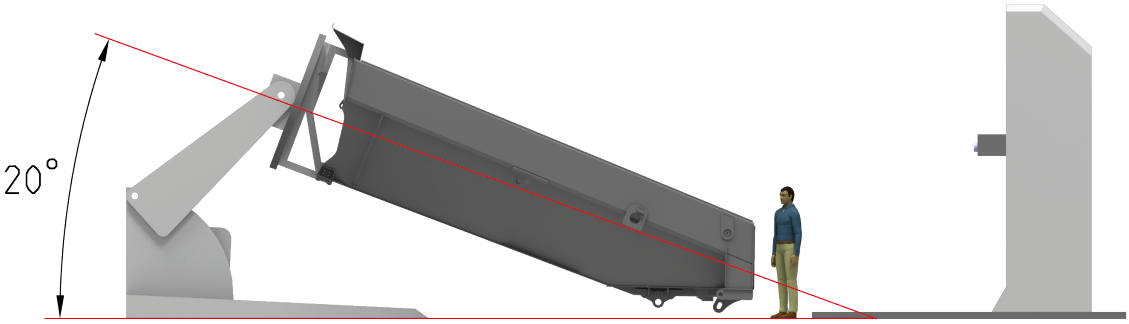


Figure 5.41: Positioner with hauler body tilted for manual ergonomic loading of wear plates.

The headstock is also equipped with a front adapter designed to fit all current bodies. The adapter is illustrated in Figure 5.42. The bodies are mounted to the adapter using horizontal locking pins through the cap support and vertical locking pins through the bottom plate, fixating the workpiece in all six DOF. The adapter can be mounted to the positioner in multiple ways, depending on how the positioner is designed.

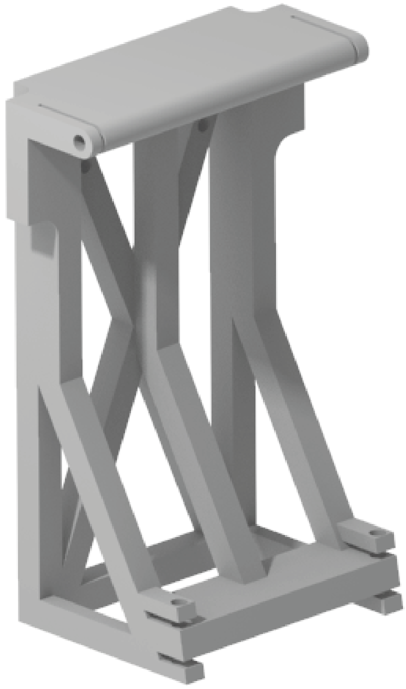
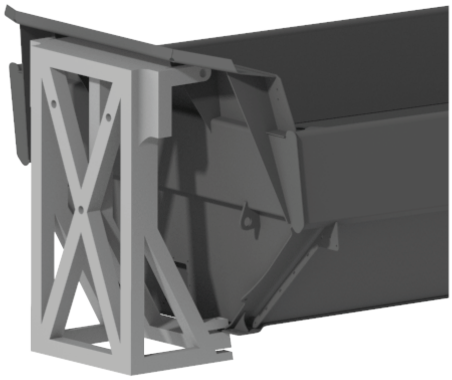
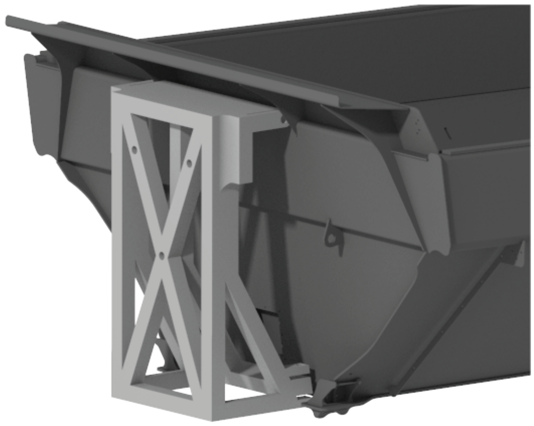


Figure 5.42: The designed flexible front adapter.

An example of how the positioner is mounted to the body is illustrated in Figure 5.43. The adapter has two different slots for locking in the bottom plate for maximum height adaptability between the different bodies. The vertical locking pins then go up or down depending on which slot is used. With only one slot, the adapter would be too short or too long for some bodies.



(a)



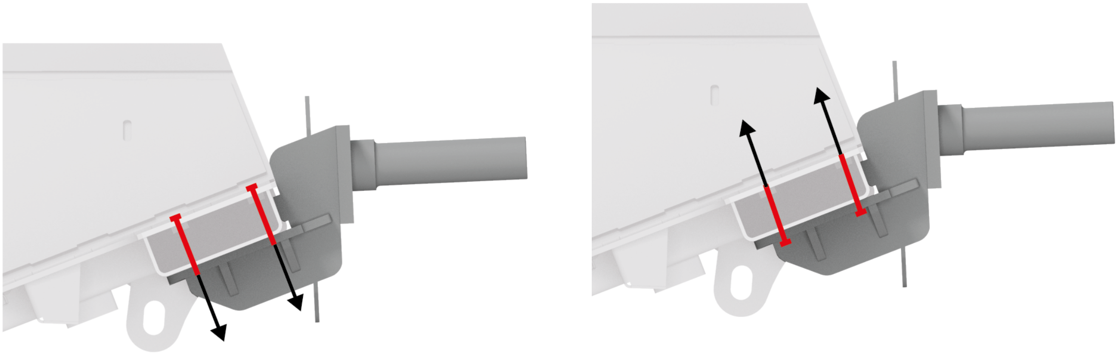
(b)

Figure 5.43: The difference in mounting between AH1 and AH6 bodies, with (a) upper attachment and (b) lower attachment.

The following design modifications need to be made for this adapter to fit all different bodies. The changes have been discussed with VCE and look fully possible to implement at an initial stage.

- Extended bottom plate.
- Holes in the bottom plate for the vertical locking pins.
- Fixed distance between the two middle cap supports.
- Holes in the two middle cap supports for the horizontal locking pins.
- For the AH6, the two middle cap supports need to be enlarged.

Figure 5.44 presents two possible ways of mounting the rear adapter in the chute. The adapters are mounted on the underside of the body to minimise the potential blocking of wear plate loading and welding. It is attached using bolts and threaded inserts that are already welded on the underside of the chute plate, or threads in the rear adapter. The holes in the body used for the current rear adapter are used for other suspension systems and will therefore be kept. The new holes required for the newly designed rear adapter will be added to the old ones. The pin on the adapter is resting in a cradle on the tailstock with the freedom to be tilted or rotated depending on the movement made from the headstock.

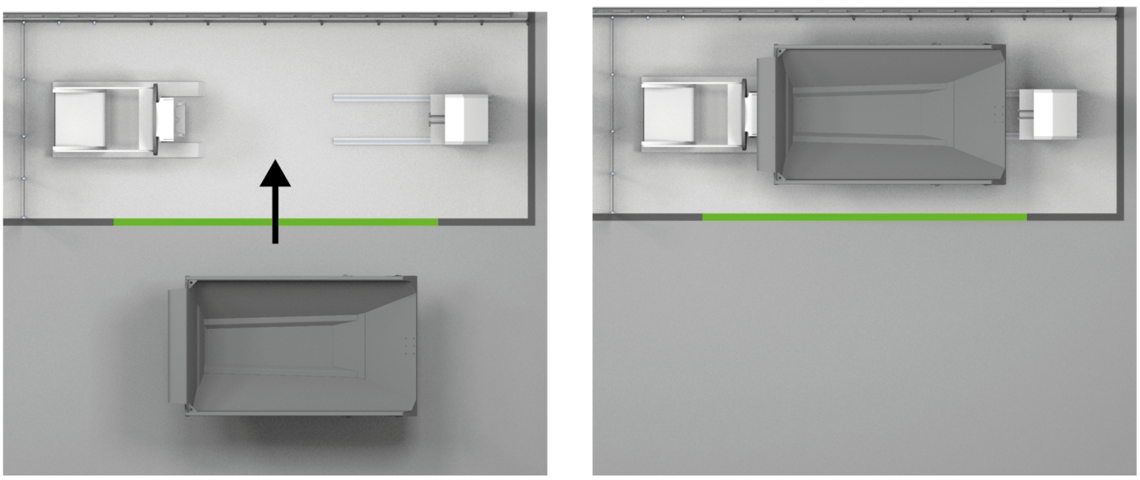


(a) (b)

Figure 5.44: Two approaches to mounting the rear adapter on the underside of the rear beam, with (a) threaded holes in the adapter and (b) threaded insert welded onto the chute plate.

The body is transported, loaded and unloaded to and off the positioner using an AGV, the process of doing this is displayed in Figure 5.45, 5.46 and 5.47. The body is lifted onto the AGV using an existing overhead crane after the body has been welded together. Future products with a weight above the maximum load for the current overhead cranes will have to be assembled on top of the AGV. In some cases, parts of the body can be assembled elsewhere and lifted onto the AGV.

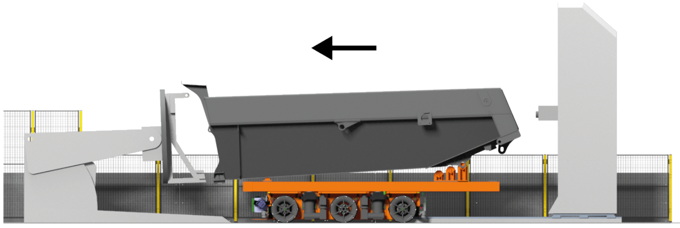
The loading process starts with the AGV positioning the body beside the positioner. After this, the AGV positions the body right between the head and tailstock in the positioner.



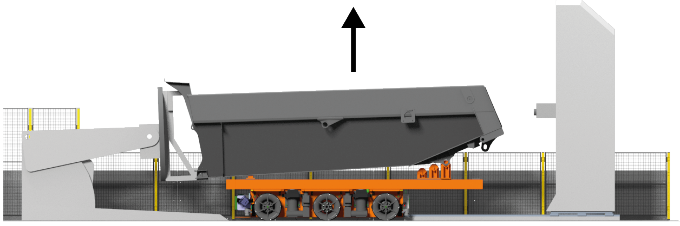
(a) (b)

Figure 5.45: AGV loading sequence (a) step 1 and (b) step 2.

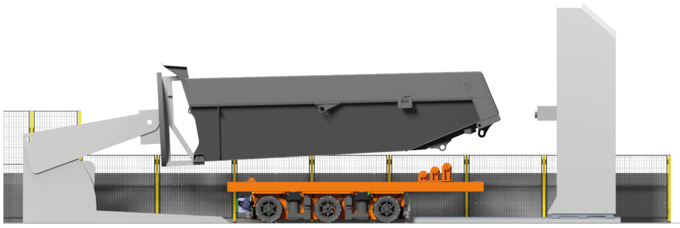
The headstock then aligns the adapter with the cap support holes and bottom plate with the right slots for that body on the adapter. Both the vertical and horizontal locking pins extend and lock the body to the adapter when the body is aligned. The body is then lifted from the AGV.



(a) Step 3



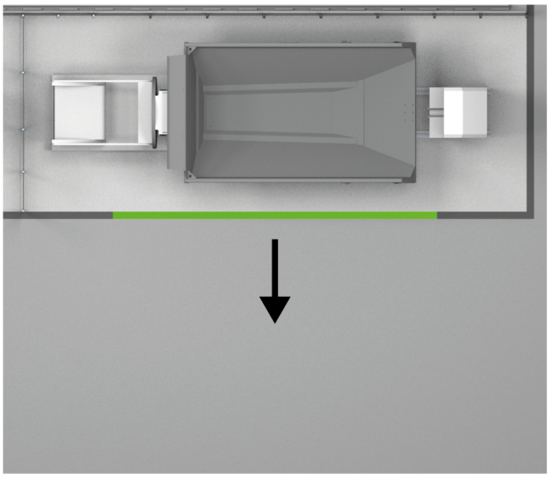
(b) Step 4



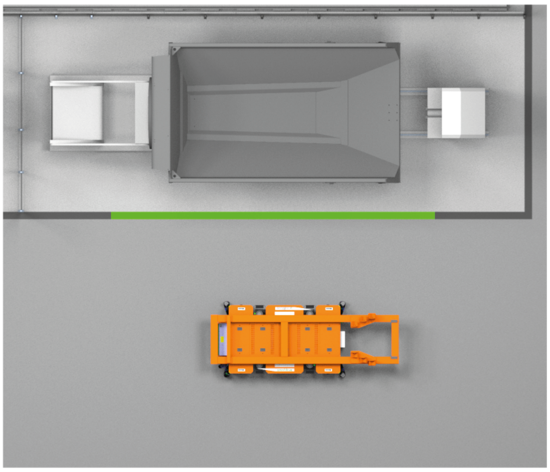
(c) Step 5

Figure 5.46: AGV loading sequence (a) step 3, (b) step 4, and (c) step 5.

When the body is lifted, the AGV can move to the side and do another job while the welding is done.



(a)



(b)

Figure 5.47: AGV loading sequence (a) step 6 and (b) step 7.

If the tailstock is used together with the headstock, two extra steps are required before the body can be lifted. Before the body is raised in step 4, the tailstock moves closer to the body with the cradle positioned lower than the chute adapter. When the tailstock is in position, the cradle moves up until the pin on the chute adapter rests inside it. The body is supported on both ends, and Steps 4 to 7 can be done as normal.

For the unloading procedure, the AGV is positioned beneath the body. The headstock then lowers the body onto the AGV and retracts all locking pins. The AGV can then drive away with the body. If the tailstock is being used, it also lowers the cradle and backs away from the body before being released and ready to move.

To minimise torque and load applied to the positioner, the centre of rotation from the positioner needs to go through the centre of mass on the body. In Figure 5.48, the centre of rotation is marked as a red line and the centre of mass as a blue dot.

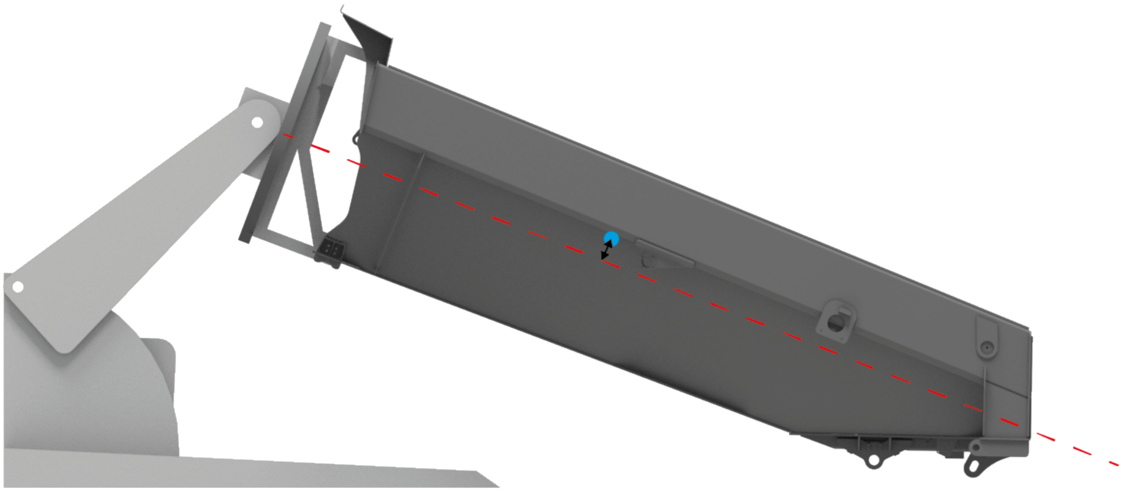


Figure 5.48: Centre of mass and rotation axle.

Since all bodies have different sizes, the centre of mass differs between them, making it difficult to hit it for all bodies accurately. In Table 5.11, the coordinates for the centre of mass for all different bodies can be seen.

Table 5.11: Centre of mass for the different bodies.

	Center of gravity		
Body	**X**	**Y**	**Z**
AH1	4264 mm	0 mm	1126 mm
AH2	4256 mm	0 mm	1180 mm
AH3	4629 mm	0 mm	1245 mm
AH4	4584 mm	0 mm	1346 mm
AH5	4584 mm	0 mm	1346 mm
AH6	4944 mm	0 mm	1113 mm

The coordinates are calculated from the origin of the coordinate system placed on the adapter, depicted in Figure 5.49. Since the height of the centre of mass differs between the bodies and the adapter has two different slots for mounting depending on the body's height, it is challenging to align the positioner rotational axis with the centre of mass for all bodies. Therefore a mean value has been calculated based on the different heights for the centre of masses. The mean is 1226 mm, which is where the positioner's rotational axis should go through on the adapter to minimise the torque and load on the positioner for all bodies.

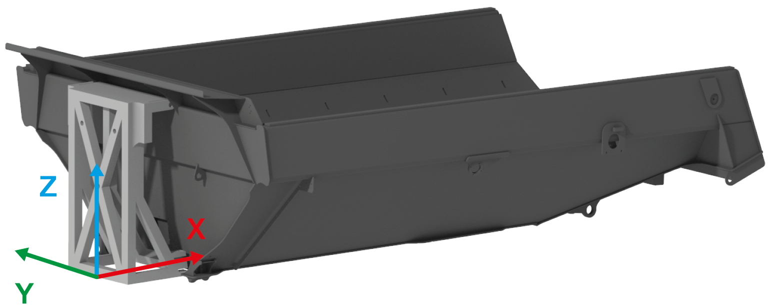


Figure 5.49: The position of the coordinate system is used to calculate the body's different centres of masses.

5.5.4.3 Concept 39

Figure 5.50 illustrates the positioner concept in Concept 39.

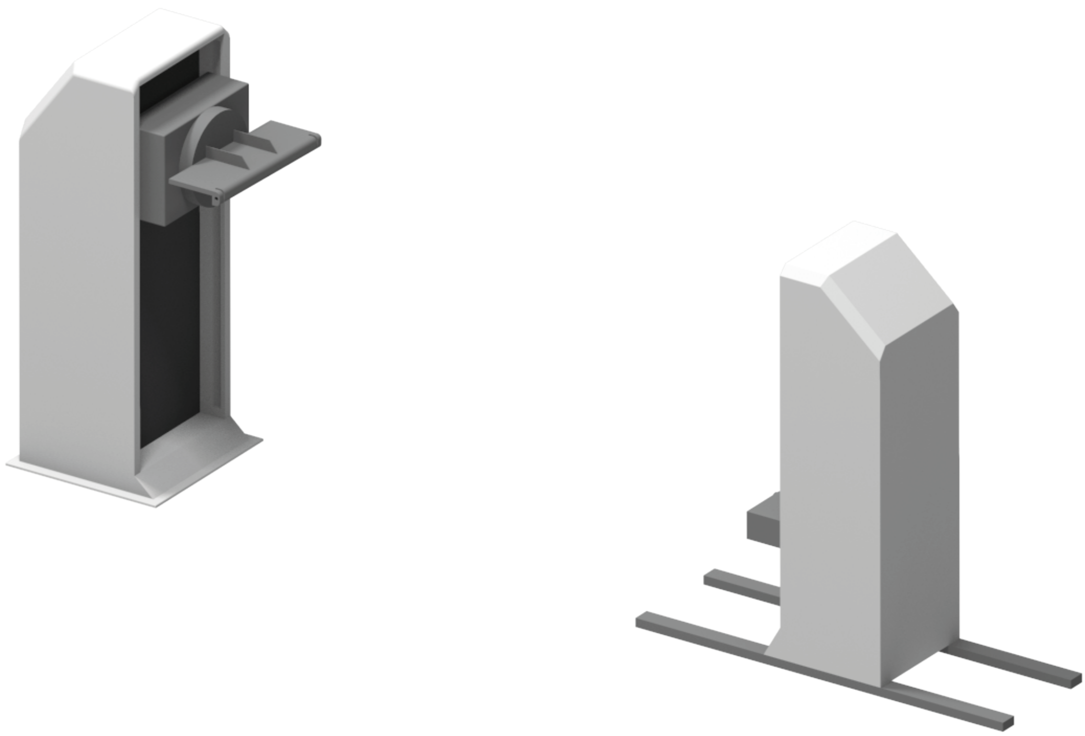
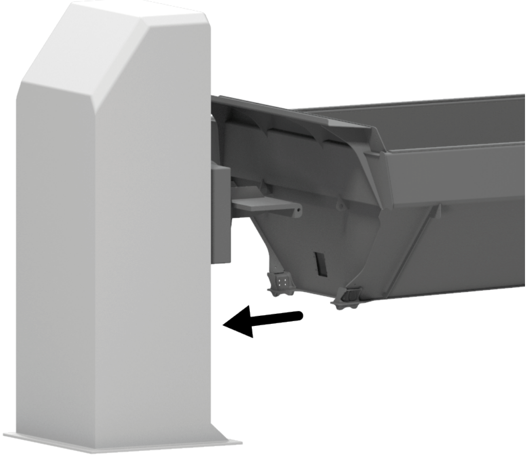
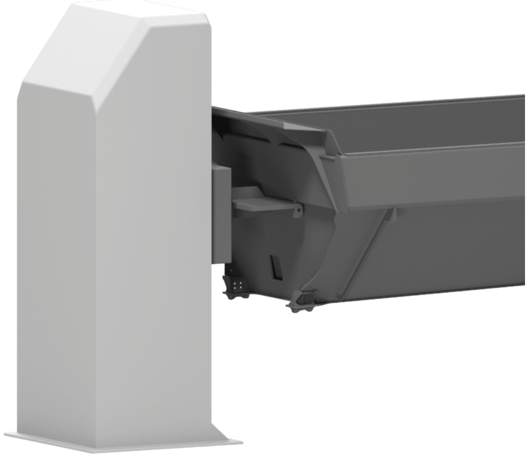


Figure 5.50: Overview of the positioner in Concept 39.

This concept uses the same suspension system as VCE uses for their bodies today. The headstock has two slots with horizontal locking pins extending out into two ears welded onto the front of the body. The ears are slotted in, and the holes are aligned before the locking pins extend. The locking pins lock on both sides of the ear for maximum robustness and ensure that the pins do not bend over time. The procedure is illustrated in Figure 5.51.



(a)



(b)

Figure 5.51: The headstock suspension system with two horizontal locking pins illustrates (a) step 1 and (b) step 2 of the attachment procedure.

At the back of the body, the same tailstock and chute adapter as in Concept 32 is used, illustrated in Figure 5.52. The tailstocks DOF is surge and heave, which is needed for pitching and fitting bodies of different lengths into the positioner. For all other movements, the tailstock works as a slave following the movement from the headstock.

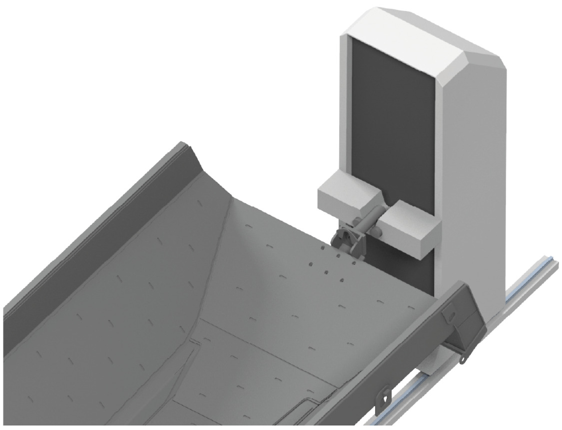
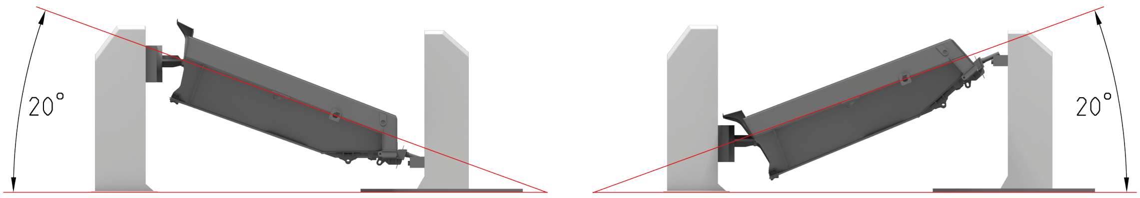


Figure 5.52: The tailstock suspension system with the beam resting in its cradle.

The positioner has three degrees of freedom heave, roll and pitch. Each stock can move the body up and down, the pitch is done through a separate heave on each stock forcing the body to tilt. The roll is done through rotation of the body from the headstock. The required 20° tilt in both directions is displayed in Figure 5.53.



(a) **(b)**

Figure 5.53: The head and tailstock height for (a) 20° pitch and (b) -20° pitch.

The tailstock must move closer or further away from the headstock for tilting and other movements, depending on the movement. In Figure 5.54, the red arc visualises the reach of the chute adapter when mounted to the headstock and tilting. The cradle's reach is pictured with the green area. The red arc and the green area need to intersect for the body and the tailstock to stay connected. During tilting and other motions, the tailstock can move the cradle vertically and its entire body horizontally to keep the body and tailstock connected.

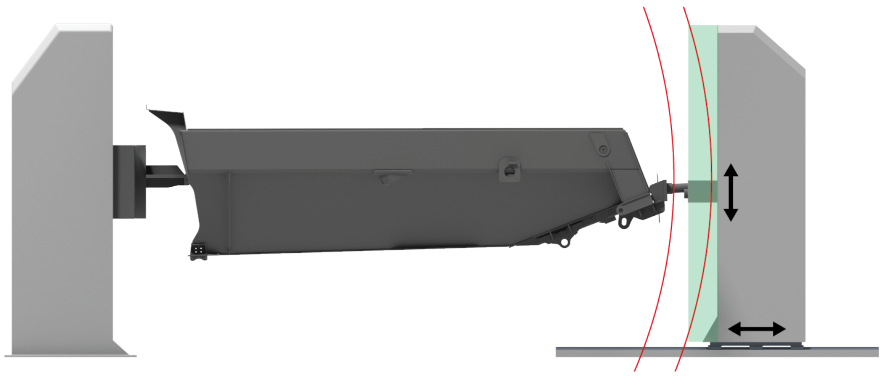
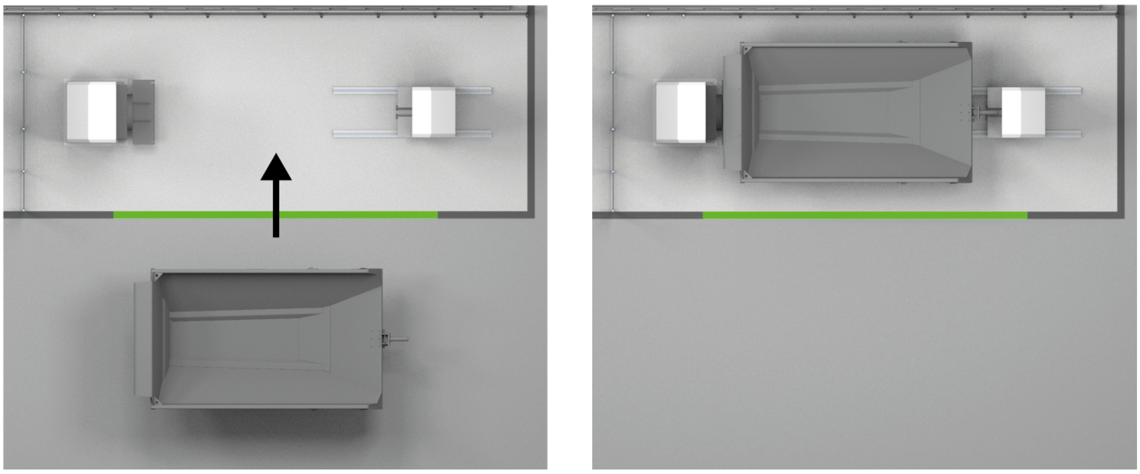


Figure 5.54: The red arc and the green area visualise the areas that need to intersect during tilting for the body to stay connected to the tailstock.

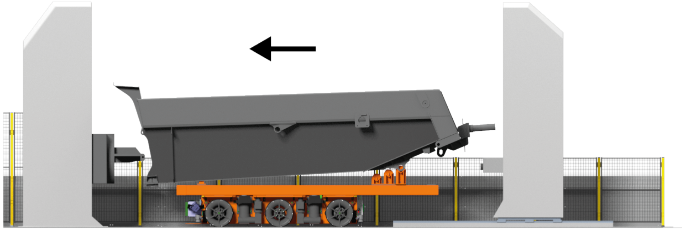
The procedure for loading a body is illustrated in Figure 5.55, 5.56 and 5.57. The body is first lifted on an AGV using an overhead crane and driven to the positioner. Future products too heavy for the crane might have to be lifted in parts and assembled on top of the AGV. This procedure is the same as in Concepts 32. When the body is on the AGV, the body is first positioned beside the positioner. The AGV then positions the body between the head and tailstock, aligning it above the slots on the headstock.



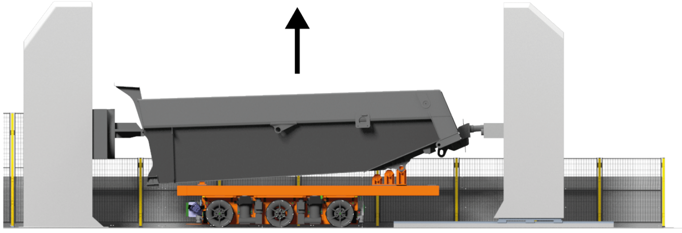
(a) Step 1 (b) Step 2

Figure 5.55: AGV loading sequence step 1 and 2.

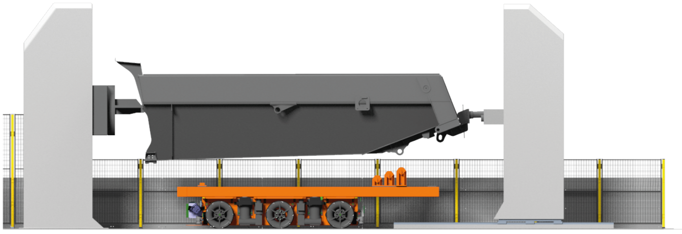
The headstock is then moved upwards until the ears on the body align with the slots, and extend the horizontal locking pins locking the body in the front. Simultaneously the tailstock moves closer to the body if necessary and moves the cradle upwards until the chute adapter rests on it. The body is now locked on both ends.



(a) Step 3



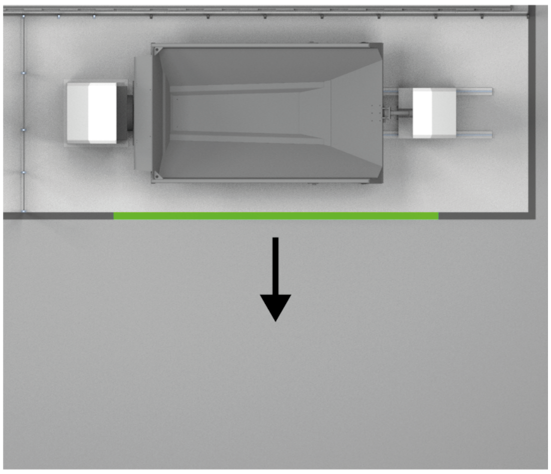
(b) Step 4



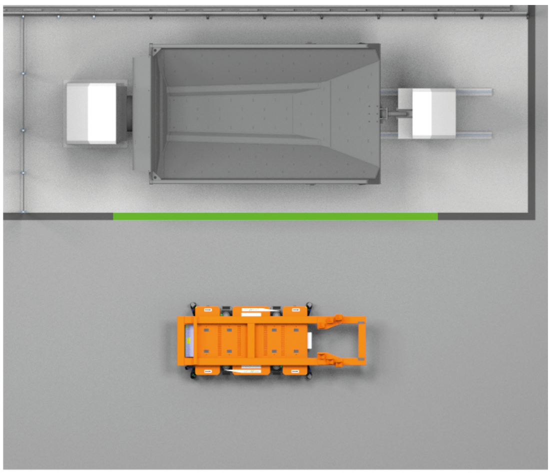
(c) Step 5

Figure 5.56: AGV loading sequence step 3, 4 and 5.

Both the head and tailstock are then moved upwards lifting the body. The AGV can then be moved to the side finalising the procedure.



(a) Step 6



(b) Step 7

Figure 5.57: AGV loading sequence step 6 and 7.

When the welding is done, the AGV drives in beneath the body. The positioner lowers the body, placing it on top of the AGV, retracts its locking pins, and lowers the tailstock cradle, releasing all attachment points. The AGV can then drive away with the body.

5.5.5 Workpiece Positioner Selection

When comparing the workpiece positioner concepts, it comes down to a trade-off between investment cost, flexibility and ergonomics. Concept 32 is more flexible and ergonomic for the workers compared to Concept 39, but it is also more expensive. The headstock solution will have an investment cost of approximately 3 600 000 SEK and the tailstock a cost of roughly 1 000 000 SEK, resulting in a total investment cost of 4 600 000 SEK. Both the head and tailstock in Concept 39 cost around 2 000 000 SEK in total. Table 5.12 presents the relative advantages and disadvantages identified for each concept.

Table 5.12: Relative advantages and disadvantages comparison between the two final concepts.

	Advantages	**Disadvantages**
Concept 32	Flexible	Expensive
	AGV unloading/loading	Smaller product modifications
	Ergonomic	Complex HS/TS synchronisation
		Firmer attachment to the floor
Concept 39	Cheap	Less flexible
	AGV unloading/loading	Less ergonomic
	No product modifications	

When considering all of these aspects, it is clear that the extra benefits that come with Concept 32 is not worth the additional cost. Therefore Concept 39 will be the final positioner concept used and modelled in the final production concept.

5.6 Production Concept

Combining the results from the robotics and workpiece positioner concept generation, evaluation, and selection, yields a final production concept. The production concept is presented in this section.

5.6.1 Model

The production concept model developed and modelled according to the previous results is presented in this section. Figure 5.58, 5.59, 5.60, 5.61, and 5.62 shows an overview of the final compiled production concept, considering both the robotics and workpiece positioner. The production cell will be enclosed in a housing with fume extraction, diminishing the need for surrounding machine protection and fume extraction hoods on the gantry. The green areas illustrate the gates and doors of the environment housing and production concept. The key dimensions of the production concept are highlighted in Appendix M.

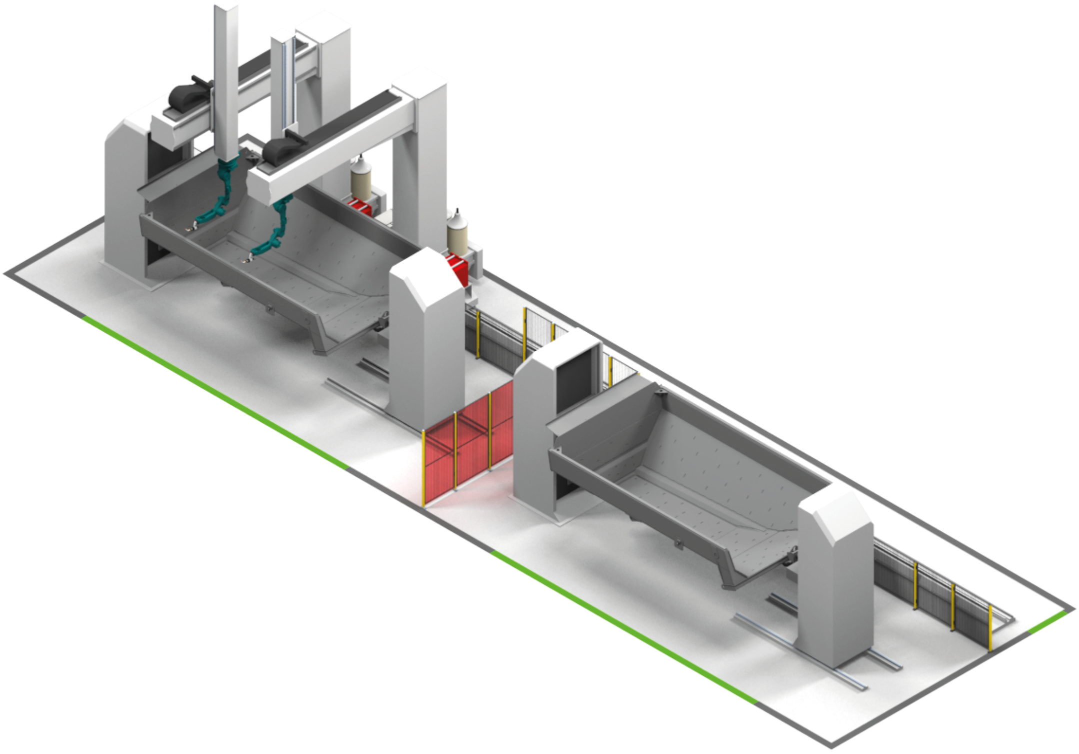


Figure 5.58: Overview of the production concept.

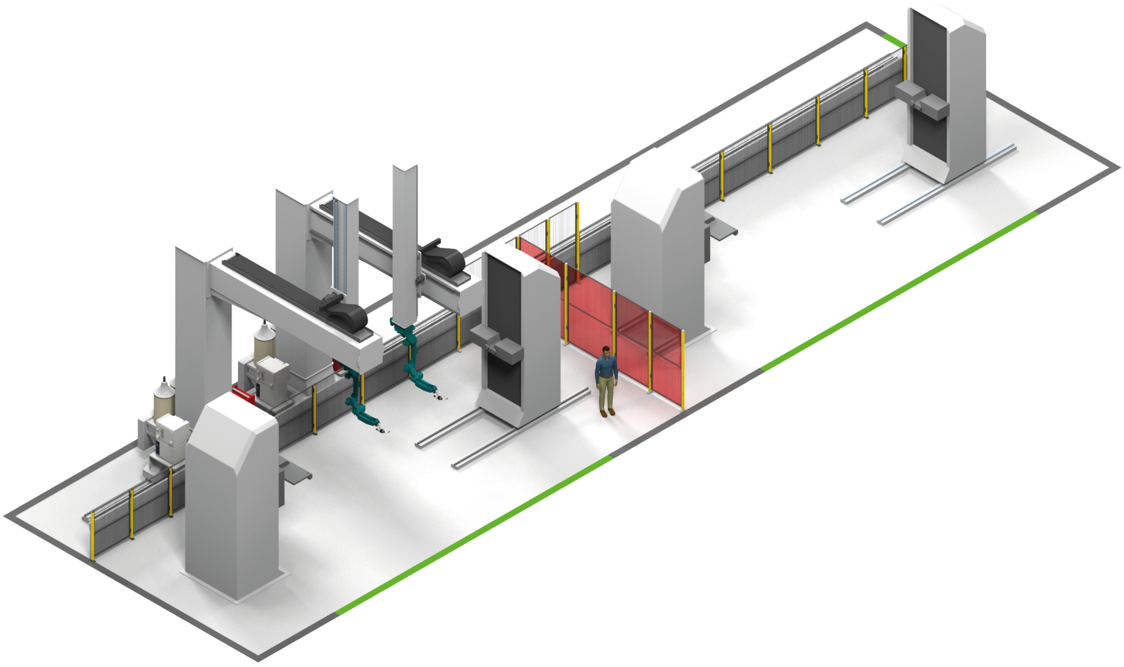


Figure 5.59: Overview of the production concept.

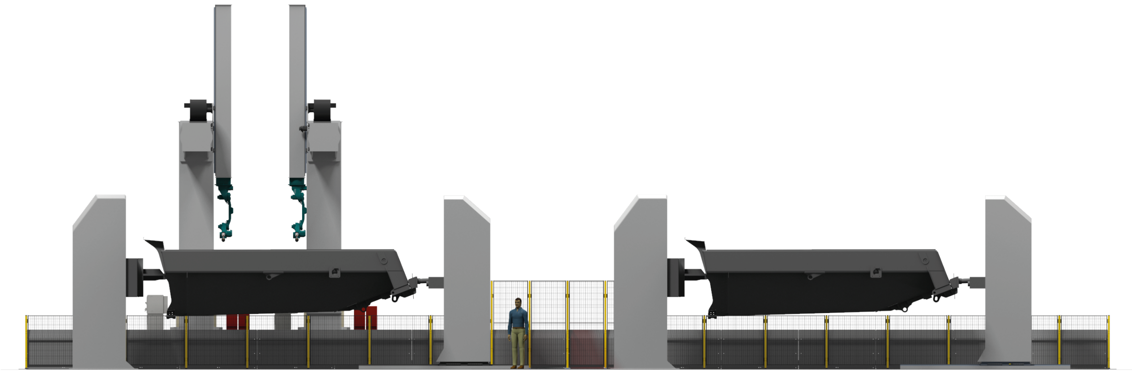


Figure 5.60: Front view of the production concept.

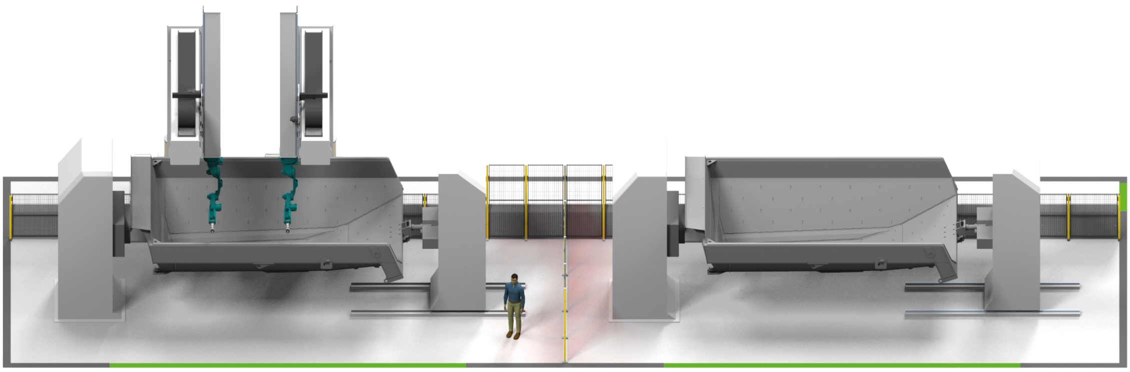


Figure 5.61: Top front view of the production concept.

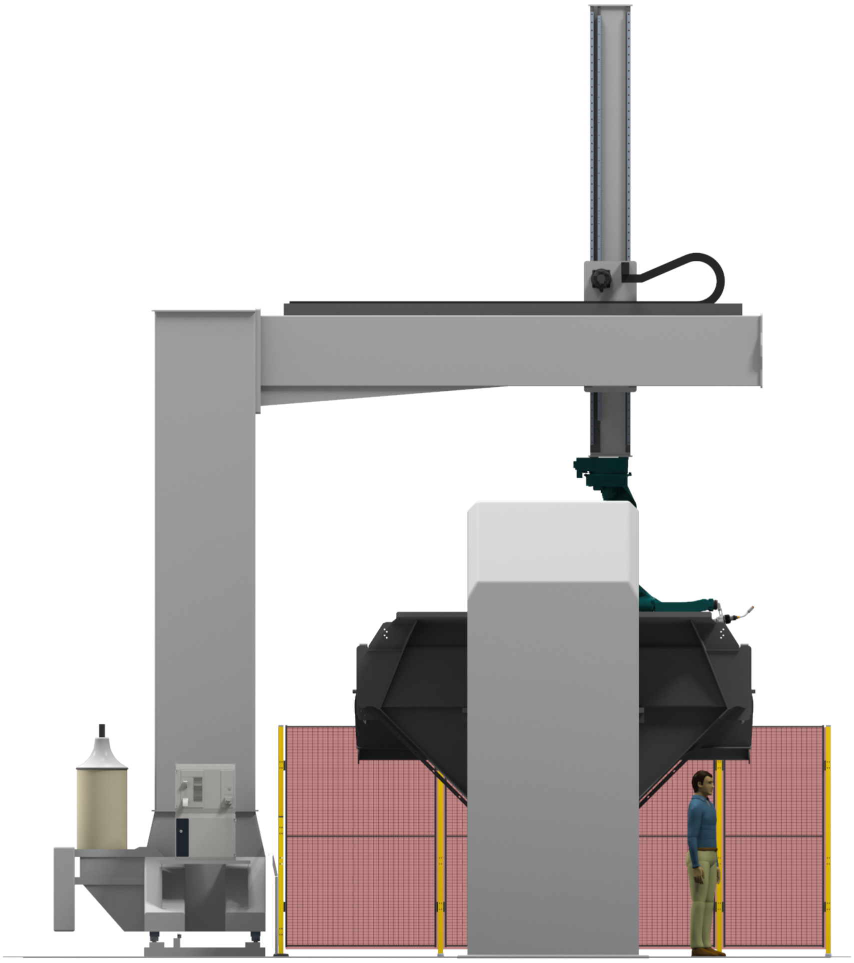


Figure 5.62: Side view of the production concept.

The production concept also includes an AGV to tend the workpiece positioner, as Figure 5.63 illustrates.

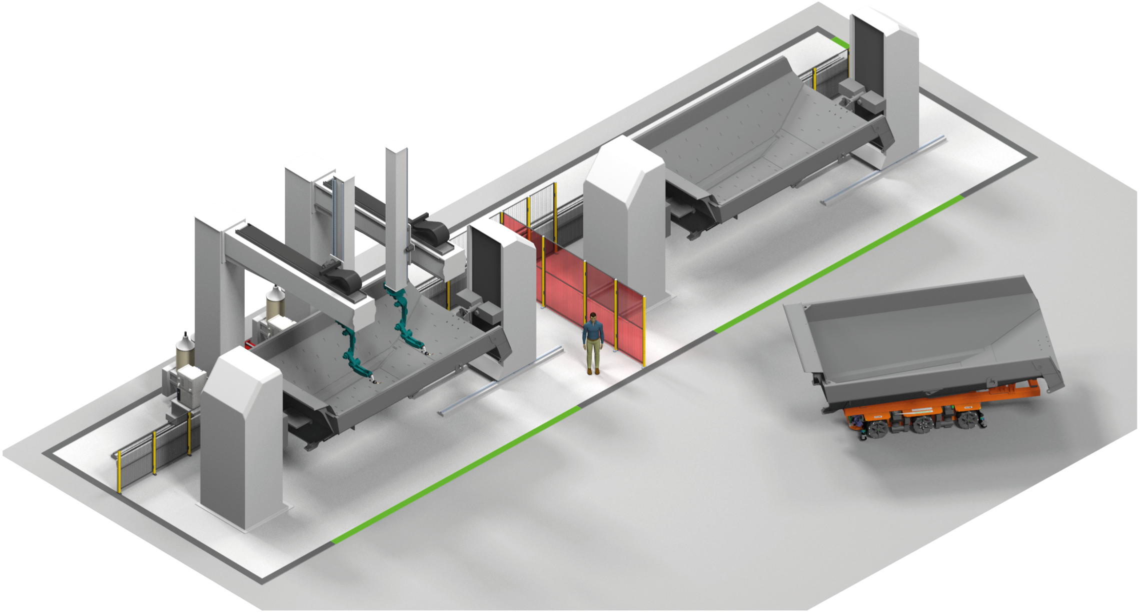


Figure 5.63: Overview of the production concept with suggested AGV solution.

The robot and pillar gantry beam positions welding a tilted hauler body are illustrated in Figure 5.64 and 5.65. This is one of the lowest weld location and position welded in, and lie on the boundary of both the work envelope and the largest hauler body motion envelope.

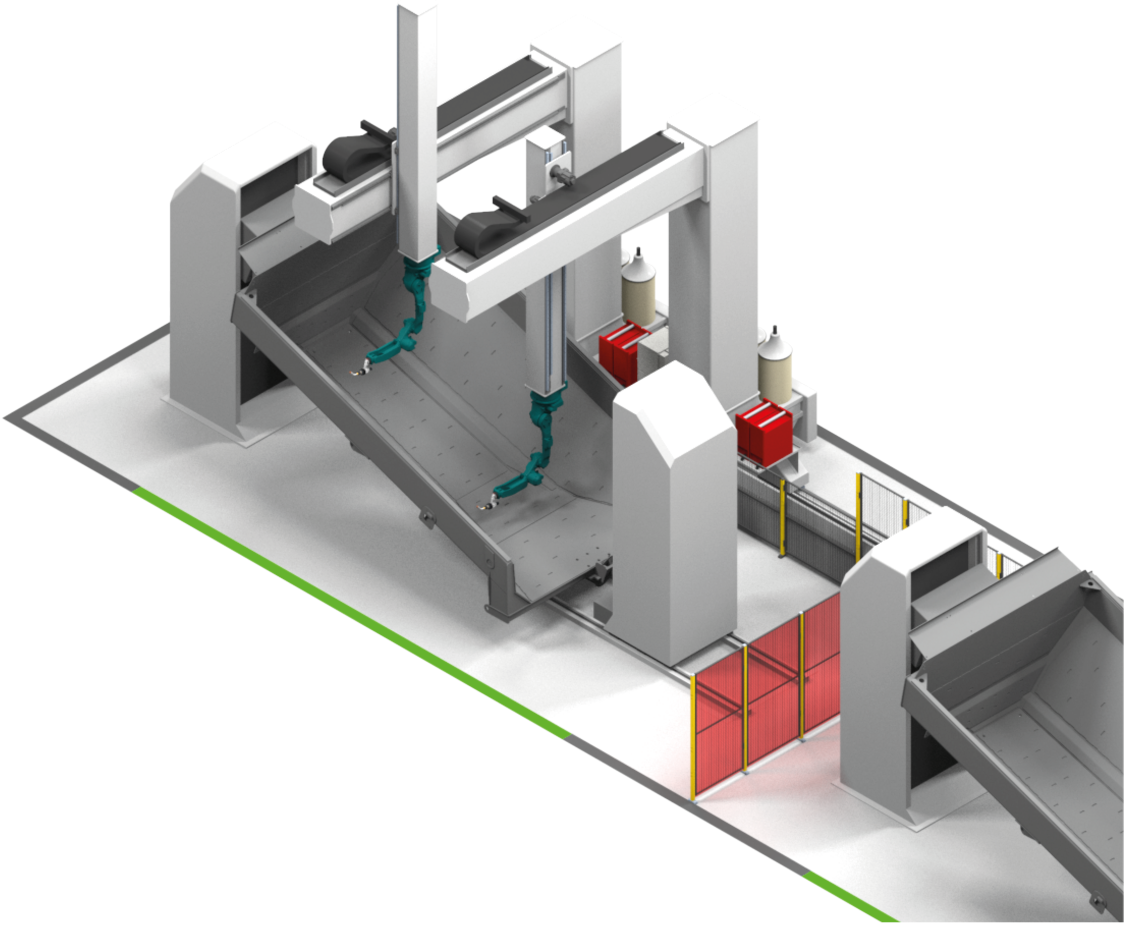


Figure 5.64: Overview of the robot reach when welding a tilted hauler body, with Z beam fully extended.

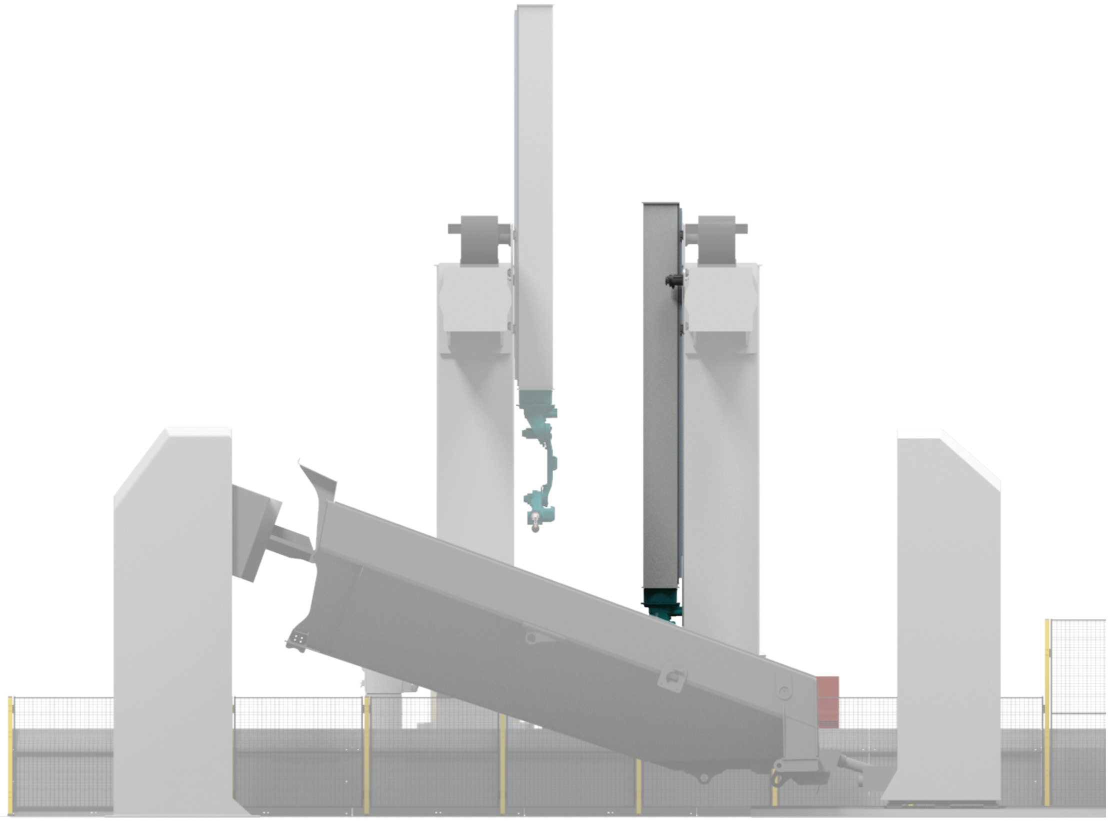


Figure 5.65: Front view of the robot reach when welding a tilted hauler body, with Z beam (highlighted) fully extended.

Furthermore, Figure 5.66 illustrates a tilted position combined with rotation.

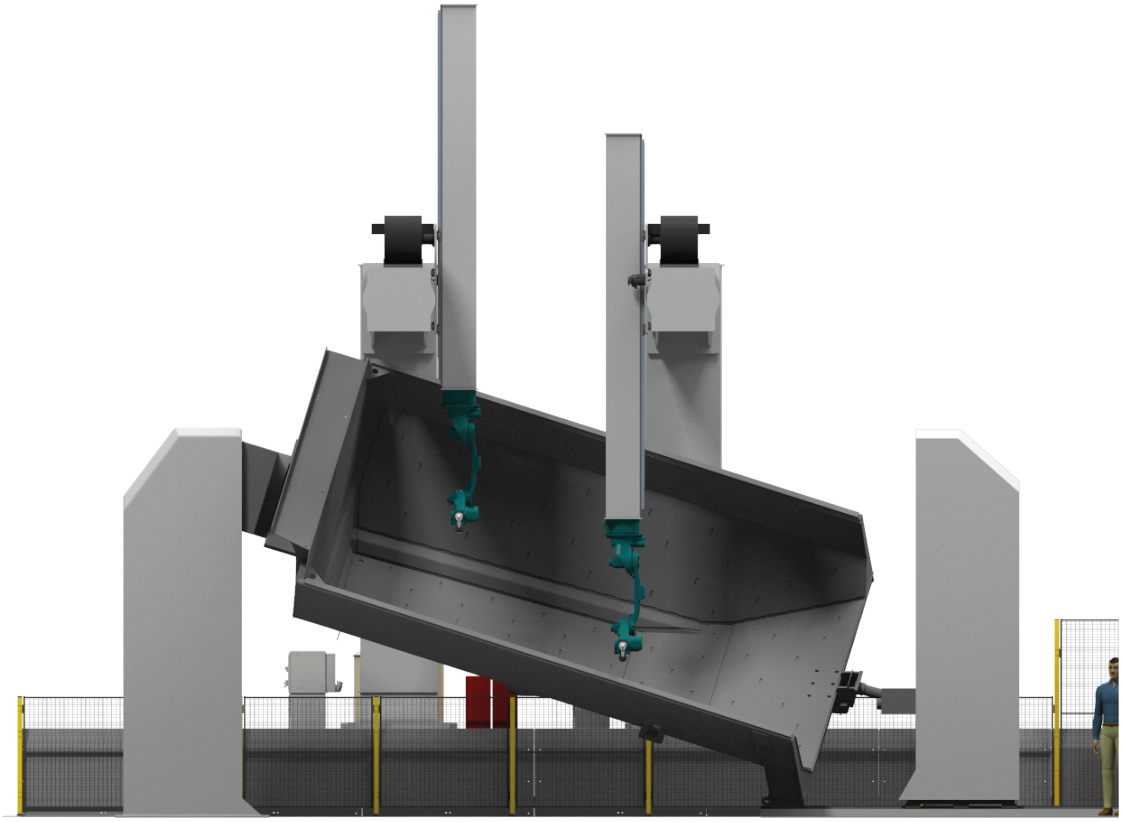


Figure 5.66: Front view of the production concept when welding a tilted and rotated hauler body.

Furthermore, Figure 5.67 illustrates the theoretically largest potential motion envelope for all current and future products. The illustration also shows that the beam lengths and stroke lengths are sufficient for welding all products in the required positions. The clashes with the floor and pillar gantry are irrelevant since welding will never be conducted in those positions, and software restrictions will be implemented to eliminate the risk of manipulating the hauler body to cause a collision.

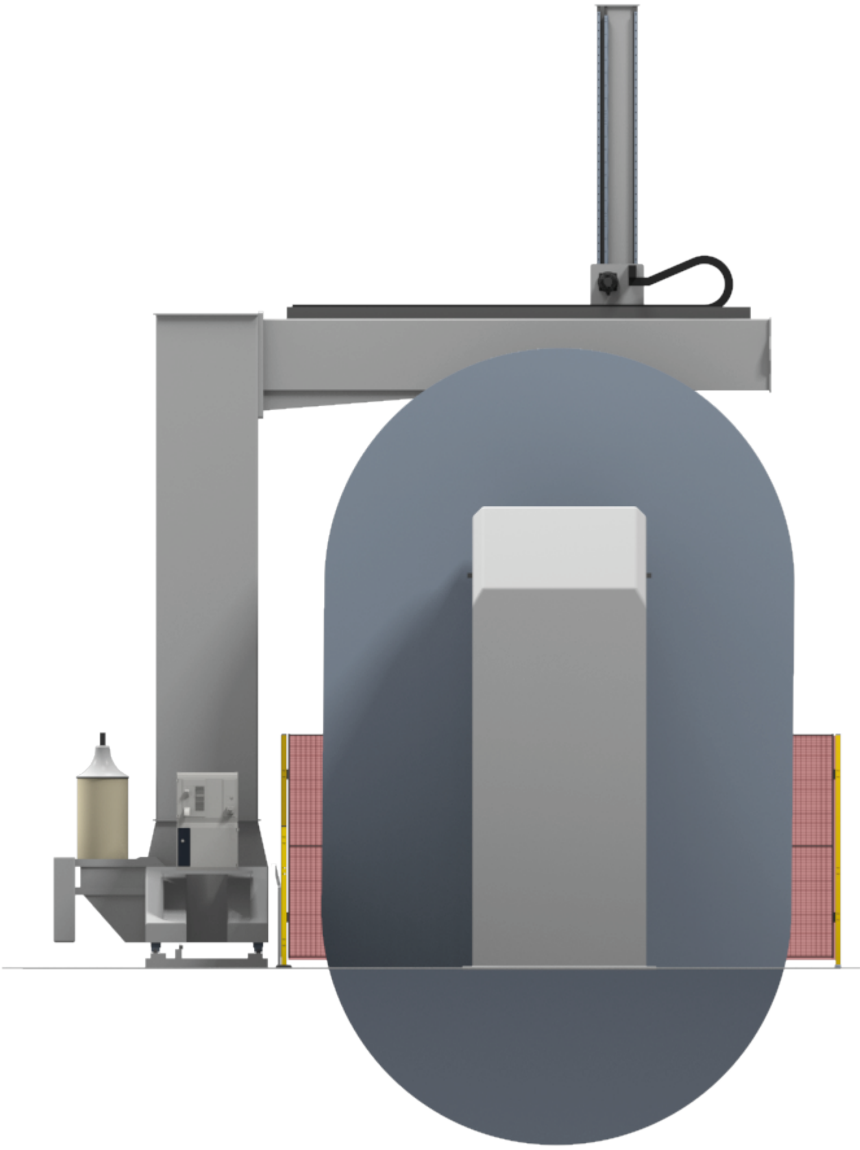


Figure 5.67: Side view of the production concept with the largest possible product motion envelope.

Figure 5.68 and 5.69 illustrates the design of the gantry pillar and external axes solutions. The power supply, wire barrel, and robot controller will be mounted on the carriage to shorten the lengths of the cables needed and the feeding length of the welding electrode.

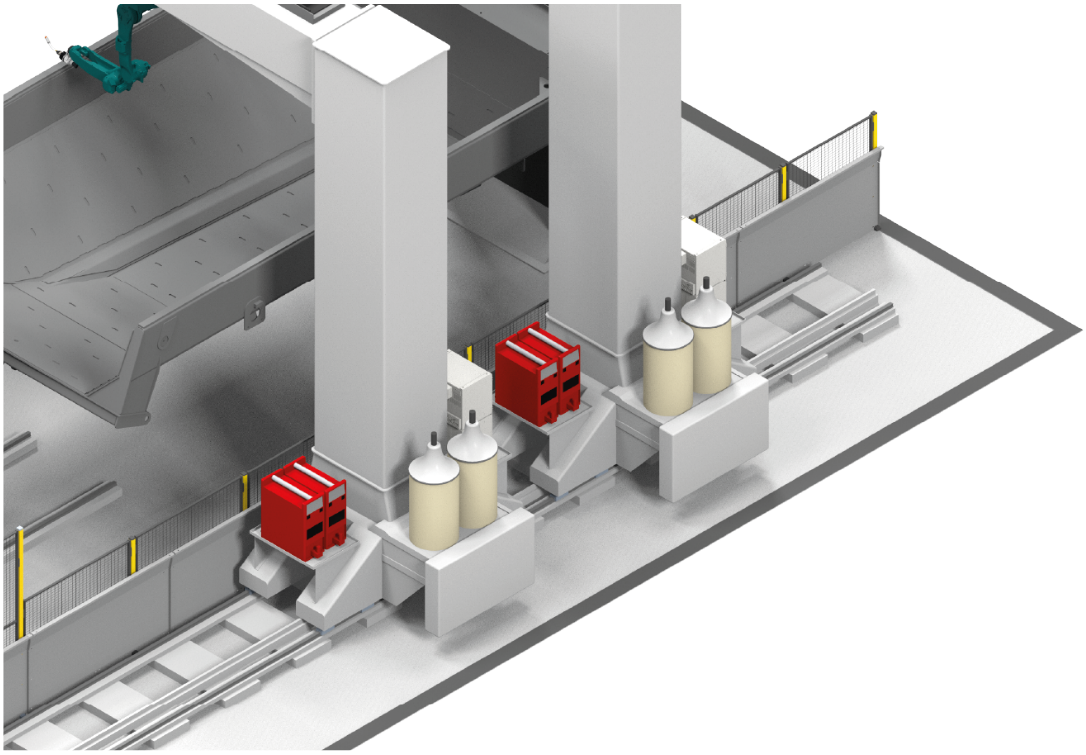


Figure 5.68: Close-up of the pillar gantry, with power supplies, robot controller, and wire barrels mounted on the carriage.

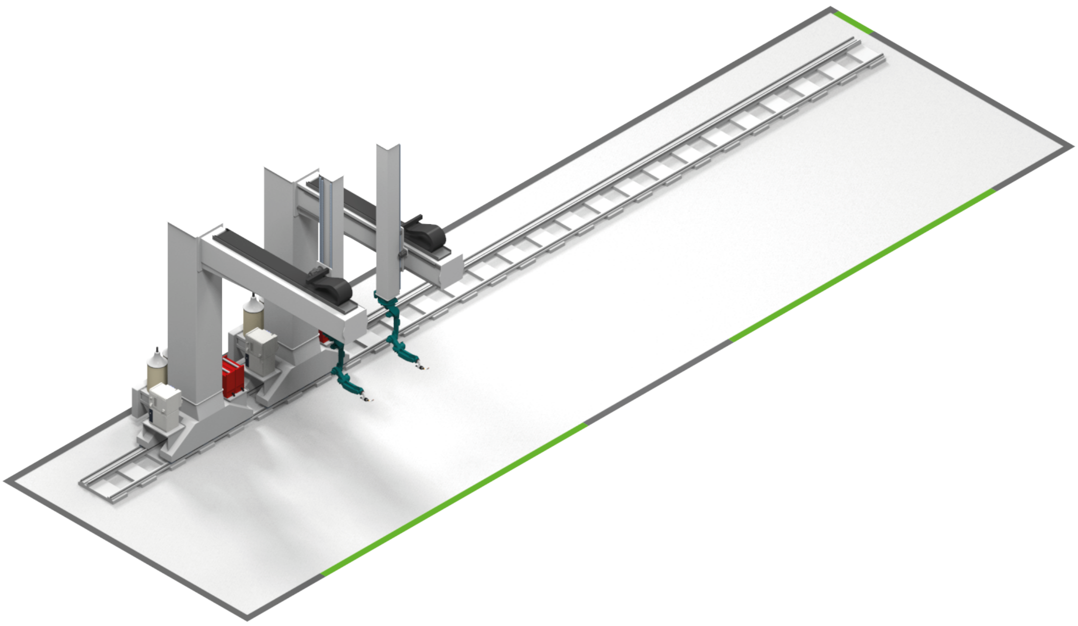


Figure 5.69: Overview of the pillar gantry concept.

Figure 5.70 and 5.71 illustrates the machine guarding designed specifically for this cell. The machine guarding contains a lower steel sheet protection combined with a mesh panel along the track, with a height of 1,40 m. This will protect the operator from accessing the gantry track cable chain while the robots operate in the second part of the cell. It will also protect the exposed gantry track components from debris and welding sparks. Between the two cells, a higher mesh panel with welding curtains with a height of 2,40 m is installed to protect the operator while performing manual work in part of the cell that is not operational.

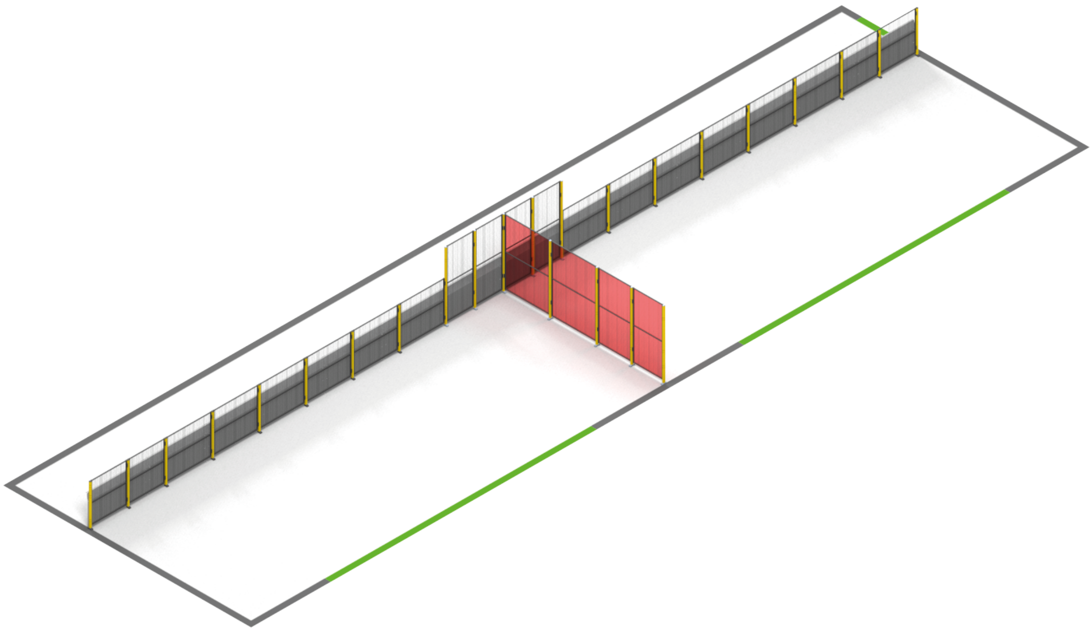


Figure 5.70: Overview of the machine guarding placed inside the fume extraction cell housing, designed according to the Machine Directive.

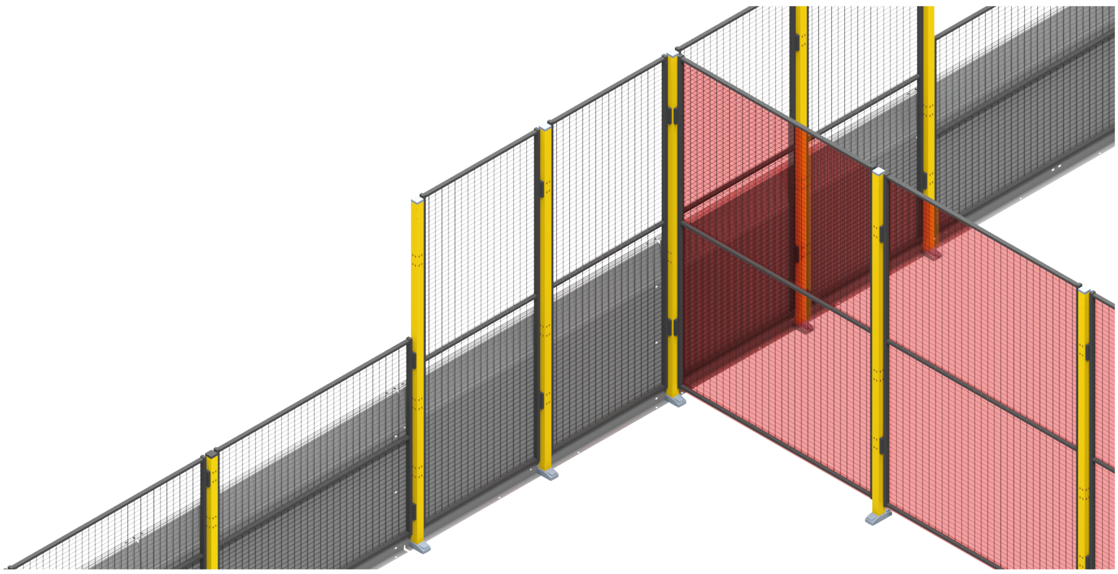


Figure 5.71: Close-up view of the machine guarding, with the mesh panel, metal sheet panel, and transparent weld protection curtain.

5.6.2 Production Preparation and Programming

Based on the selected programming solutions, a workflow concerning the production preparation and programming has been produced concerning the current state at VCE. This vision will help VCE significantly reduce the time spent on offline programming and enables automatic weld trajectory planning and optimization. Figure 5.72 describes the proposed future production preparation process, where the red boxes indicate actions performed by IPS.

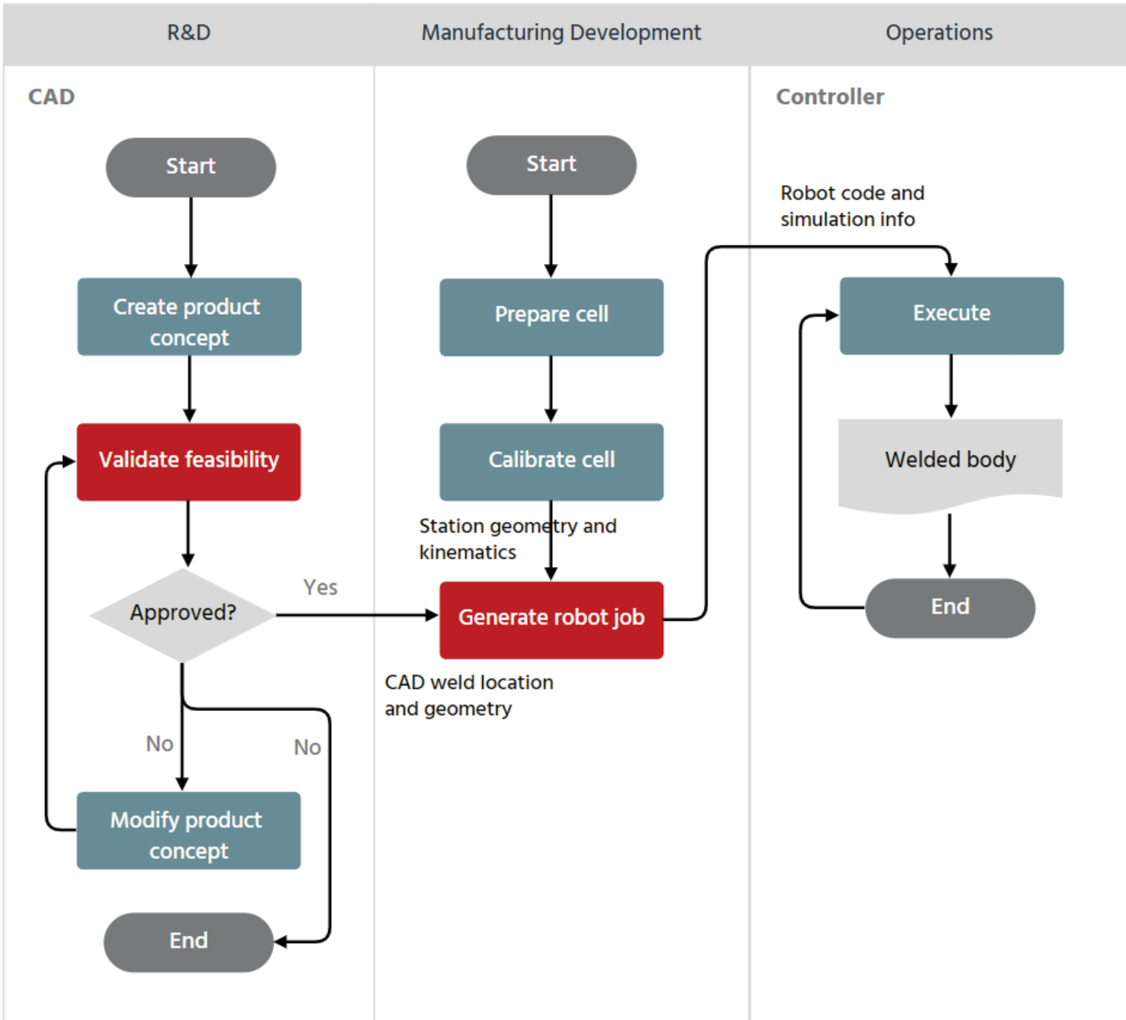


Figure 5.72: Proposed future production preparation and robot programming process, with IPS managed processes in red.

Beyond this, the proposed approach to automatic generation of robot jobs is described more in-depth in Figure 5.73.

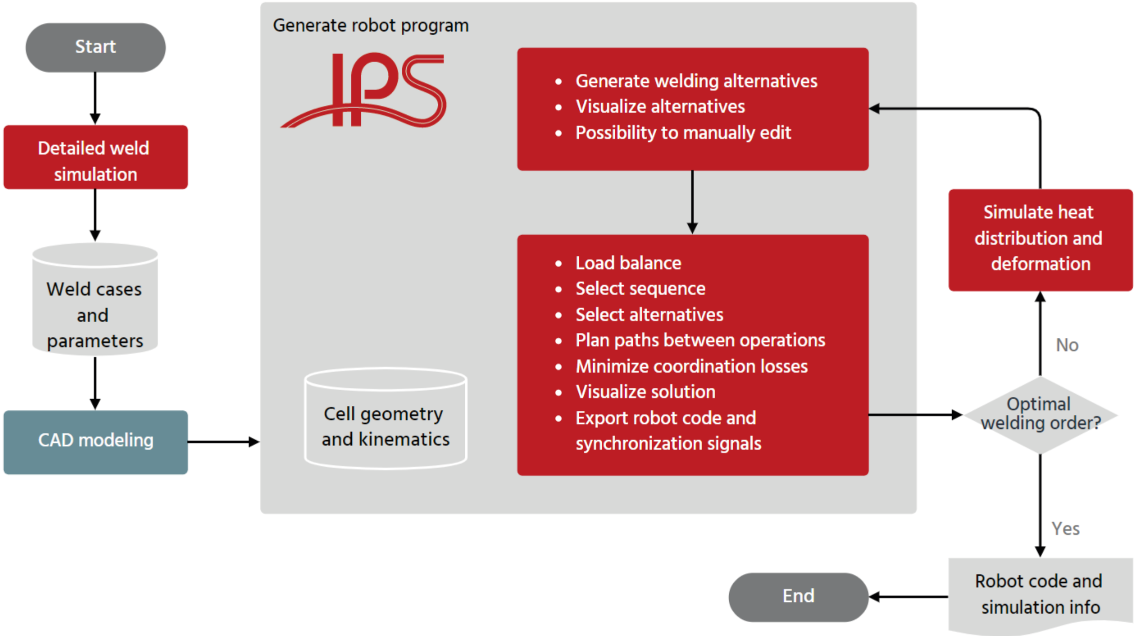


Figure 5.73: Close-up of the generation of robot programs, with processes managed by IPS in red.

5.6.3 Investment Calculations

According to the cost split up in Table 5.13, the resulting cost for the final production concept is 17 800 000 SEK.

Table 5.13: Production concept investment cost split up.

Description	**Price**	
2 pcs Headstock + Tailstock	4 000 000,00	SEK
1 pc AGV	5 000 000,00	SEK
Welding Equipment	2 200 000,00	SEK
Fume Extraction Housing	1 500 000,00	SEK
Gantry	2 100 000,00	SEK
Installation and Training	1 100 000,00	SEK
Robots	900 000,00	SEK
Engineering and Integration	1 000 000,00	SEK
Total	**17 800 000,00**	**SEK**

The computed and forecasted annual net income of the proposed investment is about 4 245 000 SEK. The resulting ROI is 23,9% annually and the investment has an estimated payback period of 4,2 years. However, this only accounts for the net savings concerning the reduced costs comparing man-hours and machine hours. The importance of also considering additional hard-to-measure aspects such as improved ergonomics and work environment, improved safety, and reduced time-to-market cannot be emphasized enough. All added values are presented in Section 5.6.6.

5.6.4 Production Flow

The production concept will enable a standard flow with a separate after flow for customer-specific options. This will increase the capacity and simplify operations. As illustrated in Figure 5.74, the production concept will add two new steps and stations at the end of the current production flow. After Station 7, which is the final welding in the standard flow, stations 8 and 9 will be added, which is the manual tack welding and the robot welding of all wear plate options. The current flow is further described in Section 5.1.1. The production concept will also enable the elimination of the parallel wear plate welding step conducted in a second facility.

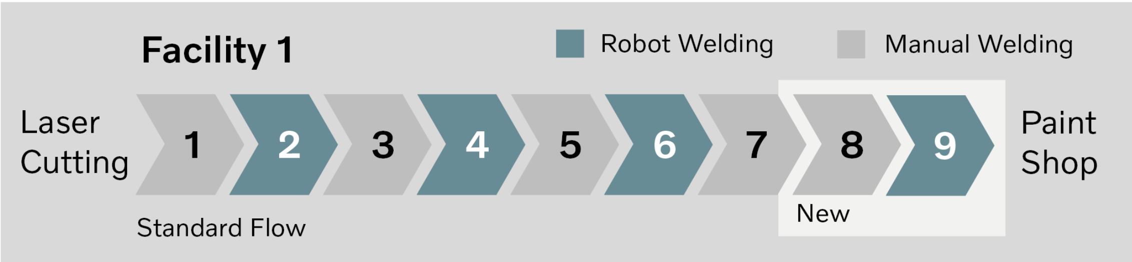


Figure 5.74: Proposed future production flow.

The layout of the production flow must also be updated, and the cell position in the facility will enable fast transport from the last process in the standard flow and transport to the paint shop. The new proposed layout is presented in Figure 5.75, including a planned extension of the current building.

Figure 5.75: Proposed future production layout.

5.6.5 Facility

The minimum height clearance needed for the robot is 9.9 m. If the roof is lower than this there is a risk of collision. The robot is rarely in its highest position, but the risk of collision should still be eliminated. The potential to slightly lower and optimize the minimum required ceiling clearance when finalizing the mechanical design, beam lengths, and stroke lengths. However, this can only and must be done in a later and more detailed project phase.

5.6.6 Added Values

With the implementation of the production concept, several improvements and added values can be expected:

- The total yearly production need for wear plate welding will theoretically be reduced from 2977,2 hours to 360,6 hours, a 88% reduction.
- Additional increased production capacity of more than 2000 hours per year (beyond the capacity for wear plate welding), for future low-volume products. This can increase the overall throughput of 1000 hauler bodies per year.
- Reduced through-put time for welding of wear plates and future low-volume products.
- Reduced manual welding from 100% to less than 10% for welding wear plates.
- Reduced Time to Market (TTM) for future products.

- Reduction of time spent on material handling related handling losses with in-cell buffer and AGV.
- Improved ergonomics, reduced manual work in strained working positions.
- Reduced risk of musculoskeletal disorders.
- All production within the same facility, no need to transport hauler bodies to the second facility.
- Increased production system flexibility. The cell can handle many different welding processes and products and enable faster commissioning of future low-volume products.
- Easier and safer workpiece positioner loading and unloading hauler bodies with AGV. Automatic loading and unloading of hauler body are also possible.
- Safer internal logistics and handling of hauler body with AGV, compared to forklifts.
- Optimized robot programs decreasing the overall cycle times by up to an estimated 25%.
- Reduction in time spent on commissioning and offline programming by up to an estimated 75%.

6
Discussion

The used forecast of future demand and production volumes on which the design capacity of the robot cell has been based are approximated by VCE. This approximation is uncertain, and the actual future demand could differentiate from the designed production capacity.

The criteria and their weighting used in the screening matrices have been set together with VCE, but there is still a subjective aspect, making it uncertain. To increase the certainty, the subjectivity of the criteria and how they are weighted would need to be minimised. Due to the uncertainty, the results of this project should be seen as an indication rather than a recommendation. Due to the uncertainty, it is possible to redo the evaluation and selection process with other aspects and weigh the evaluation differently, possibly receiving another result. This report provides enough information to perform such an iteration if the priorities are different for VCE in the future.

The produced requirement specification is simplified and adapted to a conceptual study. Detailed demands and requirements, lacking the possibility to be confirmed at this stage have not been included, such as reliability and availability.

All requirements in the requirement specification list have been achieved except for the overall work ergonomics. These criteria have been significantly improved compared to the current situation, but the process still includes some manual welding and working positions that are not acceptable according to VCE standards.

Re-programming for material deviations is hard to evaluate since the outcome concerning this highly depends on the robustness of the technology and systems implemented at a later stage. However, the proposed calibration solution will suffice on a concept level, and the requirement is therefore considered to be achieved.

The desire of having a 30° pitch of the work object is not achieved but could easily be fixed by making the head and tailstock taller. Since there was no current need to pitch more than 20°, cost and space were prioritised, resulting in a shorter head and tailstock. The lifespan and reliability demands of the positioner are hard to verify at this stage. The lifespan of the batteries in the AGV is probably shorter than the lifespan of the positioner and might need a replacement before the positioner's lifespan is depleted. Still, it should not be a problem if the positioner is designed and manufactured with this in mind and gets regular maintenance.

The tack welding times are highly speculative and dependent on the welding operator's experience. Therefore, the production concept ensures that the total tack welding time is slightly longer than the total robot welding time, to account for the fact that the tack welding time is easier to reduce than the robot welding time. Especially if a collaborative approach is adopted in the tack welding process.

The idea of moving some of the body's displacement to the headstock adapter in Concept 32 was discussed. However, this would require the adapter to grip on the long sides of the body and the front and, in turn, cover weld seams. Because of the weld seam covering, this idea was never explored further.

A possible improvement to decrease the maximum torque when moving bodies in the positioner using the designed flexible adapter in Concept 32 could be putting the positioners rotational axis close to the heaviest body's centre of mass. This would result in a lower torque for the heavier bodies and a larger distance between the positioner rotational axis and the lighter body's centre of mass, increasing the required torque for smaller bodies. Some calculations should be made here to see which solution gives the lowest maximum torque.

When looking at the investment calculation for the entire robot cell, it is important to remember that it has been solely calculated based on the estimated reduced costs comparing the man-hour and machine hour costs, or the running costs. The investment cost of procuring and implementing the production cell is also estimated based on data from suppliers and previous procurement's by VCE. This means that the robustness of the investment analysis is only moderate, and the payback period and ROI is sensitive to changes in the net income and investment cost. The additional immeasurable gains in ergonomics, work environment and improved safety, which improve the life quality of the workers and reduce the number of personnel on sick leave, should also be taken into account in a more detailed analysis. These improvements also make the workplace more attractive, making it easier to hire more competent personnel. The robot cell also removes the need to transport some bodies to the other factory, saving transportation costs. There is also no consideration of interest rates, but the investment calculation is only supposed to give a first indication of the economics of a possible implementation.

7
Conclusion

A case-specific production concept has thoroughly been produced using established methodology to analyse the state of the art and future technology, test the feasibility of alternatives, and quantify unknowns and weaknesses. The production concept includes cost-effective solutions for flexible robotics and a flexible workpiece positioner, which answers the initial problem formulations presented in Section 1.4. The production concept can also weld larger and heavier work objects than currently possible. The report also holds enough information to develop the presented concept further.

Furthermore, indications toward solutions have been presented for all identified problems in the problem specification. The initially set requirement specification has been met with the only exception of ergonomic work standards, which have improved significantly.

It can be concluded after thoroughly following concept development methodologies and theories, that a head and tailstock workpiece positioner concept is the most flexible and cost-effective solution for manipulating the hauler body.

It can also be concluded that one welding robot is enough for the current demand. Still, two robots are beneficial for ensuring future-proofness, redundancy, and optimal cycle time reduction potential. Material handling time could be reduced with an in-cell buffer. Furthermore, wear plate loading using robots is complex and not very cost-effective. Autonomous welding requires advanced sensors, calibration methods, and programming processes. The technology is not mature enough to enable cost-effective, fully autonomous welding. Investing large amounts of time and funds in developing systems to break new ground is required to reach a higher level of automation and autonomy.

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A

Generated Workpiece Positioner Concepts

Table A.1: Generated workpiece positioner concepts, subfunction 1 to 5.

Concept	1. Loading	2. Interface	3. Suspension	4. Roll	5. Pitch
Concept 1	Rail	Head/Tailstock	Bolted adapter, locking pins	Rotating pneumatic cylinder	Lifting differance
Concept 2	AGV	Hamster wheel	Gripper	Motion platform	Motion platform
Concept 3	Rail	Head/Tailstock	Bolted adapter, locking pins	Rotating hydraulic cylinders	Lifting differance
Concept 4	Overhead crane	C-positioner	Current back and front	Electric motor	Lifting differance
Concept 5	Overhead crane	Head/Tailstock	Current back and front	Electric motor	—
Concept 6	AGV	Table, (shortside)	Bolted adapter	Turntable	Positioning table
Concept 7	AGV	Table, (bottom middle)	Hooks	Turntable	Positioning table
Concept 8	AGV	Rotating lift	Bolted adapter	Turntable	Positioning table
Concept 9	AGV	Rotator	Hooks	Electric motors	Positioning table
Concept 10	AGV	Sigma Tau	Gripper	Electric motors	Motion platform
Concept 11	AGV	Swing	Hooks	Motion platform	Motion platform
Concept 12	Rail	Head/Tailstock	Current back and front	Electric motor	Lifting differance
Concept 13	Rail	Head/Tailstock	Bolted adapter, locking pins	Rotating pneumatic cylinders	Lifting differance
Concept 14	Rail	C-positioner	Bolted adapter, locking pins	Electric motor	Lifting differance
Concept 15	Rail	Head/Tailstock	Current back and front	Electric motor	Lifting differance
Concept 16	Rail	Head/Tailstock	Hooks, locking pin	Electric motor	Lifting differance
Concept 17	Overhead crane	Skyhook	Hooks	Turntable	Positioning table
Concept 18	Overhead crane	Cradle	Hooks	Turntable	Lifting differance
Concept 19	AGV	Table bottom, middle	Hooks	Turntable	Positioning table
Concept 20	Overhead crane	Table, shortside	Locking pin	Turntable	Positioning table
Concept 21	Rail	Grappling arms, longside	Hooks	Rotating pneumatic cylinders	Lifting differance
Concept 22	Overhead crane	Hamster wheel	Unique product frame	Turntables	Lifting differance
Concept 23	Overhead crane	Hamster wheel	Bolted adapter, locking pins	Positioning table	Lifting differance

Table A.1 – continued from previous page

Concept:	**1. Loading**	**2. Interface**	**3. Suspension**	**4. Roll**	**5. Pitch**
Concept 24	Overhead crane	Cradle	Hooks	Rotating hydraulic cylinders	Lifting differance
Concept 25	AGV	Table, shortside	Locking pin	Turntable	Positioning table
Concept 26	Overhead crane	Table, bottom middle	Bolted adapter	Turntable	Positioning table
Concept 27	Overhead crane	Table with track	Unique product frame	Turntable	Lifting differance
Concept 28	Overhead crane	Motion platform	Hooks	Turntable	Positioning table
Concept 29	Overhead crane	Rotator	Bolted adapter	Tracks	Positioning table
Concept 30	AGV	C-positioner	Current front and back	Rotating pneumatic cylinder	Lifting differance
Concept 31	Overhead crane	Skyhook	Bolted adapter	Turntable	Positioning table
Concept 32	AGV	Rotating lift	Locking pin	Turntable	Positioning table
Concept 33	AGV	Grappling arms, long-side	Bolted adapter	Lifting differance	Lifting differance
Concept 34	AGV	Grappling arms, shortside	Bolted adapter	Electric motors	Lifting differance
Concept 35	Overhead crane	Swing	Hooks	Turntable	Positioning table
Concept 36	AGV	Head/Tailstock, long-side	Locking pin	Lifting differance	Lifting differance
Concept 37	AGV	Head/Tailstock	Unique product frame	Rotating pneumatic cylinder	Lifting differance
Concept 38	AGV	C-positioner	Unique product frame	Rotating hydraulic cylinders	Lifting differance
Concept 39	AGV	Head/Tailstock	Bolted adapter, locking pins	Electric motor	Lifting differance
Concept 40	AGV	Rotating lift	Bolted adapter	Turntable	Positioning table

Table A.2: Generated workpiece positioner concepts, subfunction 6 to 10.

Concept	6. Yaw	7. Surge	8. Heave	9. Sway	10. Unloading
Concept 1	—	Tracks	Pneumatic cylinders	—	Rail
Concept 2	Turntable	Motion platform	Motion platform	Motion platform	AGV
Concept 3	Circular tracks	Hydraulic cylinders	Hydraulic cylinders	—	Rail
Concept 4	—	Tracks	Lifting motor	—	Overhead crane
Concept 5	—	Tracks	—	—	Overhead crane
Concept 6	Turntable	—	—	—	AGV
Concept 7	Turntable	—	—	—	AGV
Concept 8	—	—	Scissor	—	AGV
Concept 9	—	—	—	—	AGV
Concept 10	—	—	—	—	AGV
Concept 11	Turntable	—	—	—	AGV
Concept 12	Circular tracks	Tracks	Lifting motor	—	Rail
Concept 13	—	Wheels	Pneumatic cylinders	—	Rail
Concept 14	—	Tracks	Lifting motor	—	Rail
Concept 15	—	Tracks	Lifting motor	—	Rail
Concept 16	—	Tracks	Lifting motor	—	Rail
Concept 17	Turntable	Tracks	Lifting motor	—	Overhead crane
Concept 18	Turntable	Tracks	Lifting motor	—	Overhead crane
Concept 19	—	—	—	—	AGV
Concept 20	Turntable	—	—	—	Overhead crane
Concept 21	—	—	Lifting motor	—	Rail
Concept 22	Circular tracks	—	Lifting motor	—	Overhead crane
Concept 23	—	—	Tracks	—	Overhead crane
Concept 24	—	—	Lifting motor	—	Overhead crane
Concept 25	Turntable	—	Lifting motor	—	AGV
Concept 26	Turntable	—	Lifting motor	—	Overhead crane
Concept 27	Turntable	—	Tracks	—	Overhead crane
Concept 28	Turntable	—	—	—	Overhead crane
Concept 29	—	—	—	—	Overhead crane
Concept 30	—	Tracks	Lifting motor	—	AGV
Concept 31	Turntable	—	—	—	Overhead crane
Concept 32	—	—	Lifting motor	—	AGV
Concept 33	Electric motor	—	Lifting motor	—	AGV
Concept 34	Electric motor	—	Lifting motor	—	AGV
Concept 35	Turntable	—	Lifting motor	—	Overhead crane
Concept 36	—	—	Lifting motor	—	AGV
Concept 37	—	Tracks	Lifting motor	—	AGV
Concept 38	—	Tracks	Lifting motor	—	AGV
Concept 39	—	Tracks	Lifting motor	—	AGV
Concept 40	—	—	Lifting motor	—	AGV

B

Requirements Specification List

Criteria	Target Value	Evaluation/Verification	R/D
1. Robot cell			
1.1 Safety			
Safety standard feasibility	SS-EN ISO 10218-2:2011	Digital model observation	R
Fume extraction possibilities		Digital model observation	R
1.2 Performance			
Capacity standard option	6 units/week	Capacity computations	R
Capacity heavy-duty option	1 unit/week	Capacity computations	R
Capacity future products (5 year forecast)	8 units/week	Capacity computations	R
Total capacity	15 units/week	Capacity computations	R
Arc-on time per robot	70%	Computations	R
Arc-on time per robot	80%	Computations	D
1.3 Work ergonomics			
Ergonomic work standard	Volvo Group Standard STD 8003,2	Work process analysis	R
1.4 Maintenance			
Maintenance accessibility	100%	Digital model observation	R
2. Robotics			
2.1 Robot			
Reach weld seams	95%	Reachability analysis	R
Reach weld seams	100%	Reachability analysis	D
Load capacity (welding)	10 kg	Data sheet	R
2.2 Welding			
Single and twin capability	100%	Data sheet	R
Weldments in manual welding	<10%	Cycle time computations	R
Weldments in manual welding	0%	Cycle time computations	D
2.3 Safety			
Enabling safety standard	SS-EN ISO 10218-1:2011	Digital model observation	R
2.4 Performance			
Optimized paths, reduced cycle times	20%	Subjective assessment	D
Reduced programming time	50%	Subjective assessment	D
Weld quality feasibility	STD 181-0004	Subjective assessment	R
2.5 Programming			
Re-programming for material deviations	None	Subjective assessment	D
Re-programming for material deviations	Limited	Subjective assessment	R
3. Workpiece positioner			
3.1 Quality			
Minimum operating temperature	0 °C	Data sheet	R
Maximum operating temperature	30 °C	Data sheet	R
Minimum relative humidity	20%	Data sheet	R
Maximum relative humidity	80%	Data sheet	R
Exposed sensitive parts	0	Digital model observation	R
3.2 Dimensions			
Largest product length	8 m	Construction design	R
Largest product width	4,5 m	Construction design	R
Largest product height	4 m	Construction design	R
Smallest product length	5,5 m	Construction design	R
Smallest product width	2,5 m	Construction design	R
Smallest product height	1,5 m	Construction design	R
Positioner footprint	Minimized	Concept comparison	D
3.3 Interface			
Adaptability to current product design	Current bodies	Interface design	R
Adaptability to future product design	Future products	Interface design	D
Blocking of weld seams	<5%	Digital model observation	R
Blocking of weld seams	0%	Digital model observation	D

Table B.1 – continued from previous page

Criteria	Target Value	Evaluation/Verification	R/D
Block loading of wear plates	0 pcs	Digital model observation	D
3.4 Loading			
Time	Maximum 5 min	Subjective assessment	R
Time	<5 min	Subjective assessment	D
Unergonomic working positions	0	Work process analysis	R
Risk for operator injury	Minimized	Risk assessment	R
Need for overhead crane	None	Material flow analysis	D
3.5 Unloading			
Time	Maximum 5 min	Subjective assessment	R
Time	<5 min	Subjective assessment	D
Unergonomic working positions	0	Observation/Interview	R
Risk for operator injury	Minimized	Risk assessment	R
Need for overhead crane	None	Material flow analysis	D
3.6 Product cost			
Relative cost effectiveness	>80%	Cost analysis	R
3.7 Function			
Total load capacity	>=20 tons	FEM analysis	R
Minimum pitch	+/-20°	Digital model observation	R
Minimum pitch	+/-30°	Digital model observation	D
Minimum roll	+/- 180°	Digital model observation	R
Compatibility with robotics	100%	Data sheet	R
Adaptability for future facility	100%	Subjective assessement	D
3.8 Usage			
In-house experience	Yes	Current state analysis	D
Programming complexity	No unused DOF	Digital model observation	D
3.9 Reliability			
Lifespan	50 000 h	Data sheet	R
Lifespan	75 000 h	Data sheet	D
3.10 Performance			
Repeatability	+/- 0,5 mm	Data sheet	D
Repeatability	+/- 5 mm	Data sheet	R
Accuracy	+/- 0,5 mm	Data sheet	D
Accuracy	+/- 5 mm	Data sheet	R
Minimum total rotating torque	Moment of inertia	Data sheet	R
3.11 Environment			
Leakage of media (air, water or oil)	0%	Construction design	R

C

Robotics Morphological Matrix

Table C.1: Morphological matrix for the robotics concept generation.

Morphological Matrix									
Subfunction		**Solutions**							
1	**Number of Welding Robots**	1 robot	2 robots	3 robots					
2	**External Axes**	2-Side YZ Gantry	2-Side YZ Pillar Gantry	XYZ Gantry	XYZ Pillar Gantry	XYZ Pillar Gantry 2	2-Side XYZ Pillar Gantry 3	XYZ Pillar Gantry Rot Z	XYZ Overhead Gantry
3	**In-Cell Buffer**	None	1 unit	2 units					
4	**Loading of Wear Plates**	Overhead Crane	Robot with Gripper	Prepared Kit in Fixture/Jigg	Gantry Crane				
5	**Fixation of Wear Plates**	Manual Tack Welding	Robot Tack Welding	Robot with Gripper					
6	**Calibration of Nominal Positions**	Electrode Touch Sense	Gas Nozzle Touch-Sense	Laser Proximity	Laser Point Profiling	Laser Line Profiling	Laser Line Scan	Structured Light	Laser Scanning
7	**Seam Tracking**	Through-Arc	Laser	Vision	Digital Twin				
8	**Wear Plate Changes**	Offset All Walls	Offset Intermittent Walls	Increase Base Angles	Round Sharp Corners	Enlarge Slits	Reduce Wear Plate Sizes	Self-Locating Sheet	Flat Bar Redesign
9	**Weld Torch Setup**	1 Single	2 Single	1 Twin	1 Single & 1 Twin	2 Single & 1 Twin			
10	**Program Weld Location & Parameters**	Manual	Import CAD Data	Auto-Detect					
11	**Plan & Optimize Weld Paths**	Manual	Auto-Solve	Reinforcement Learning					

D

Robotics Concepts

D.1 Concept 1 - Low Tech

Table D.1: Low Tech Concept

Subfunction	Low Tech
1. Number of Welding Robots	1 unit
2. External Axes	1 pc XYZ Pillar Gantry
3. In-Cell Buffer	None
4. Loading of Wear Plates	Overhead Crane
5. Fixation of Wear Plates	Manual Tack Welding
6. Calibration of Nominal Positions	Electrode Touch-Sense
7. Seam Tracking	Through-Arc
8. Wear Plate Design Changes	Offset Intermittent Walls
	Increase Base Angles
	Round Sharp Corners
	Flat Bar Redesign
9. Weld Torch Setup	2 Single & 1 Twin
10. Program Weld Location & Parameters	Manual Offline + Online
11. Plan & Optimize Weld Paths	Manual Offline + Online

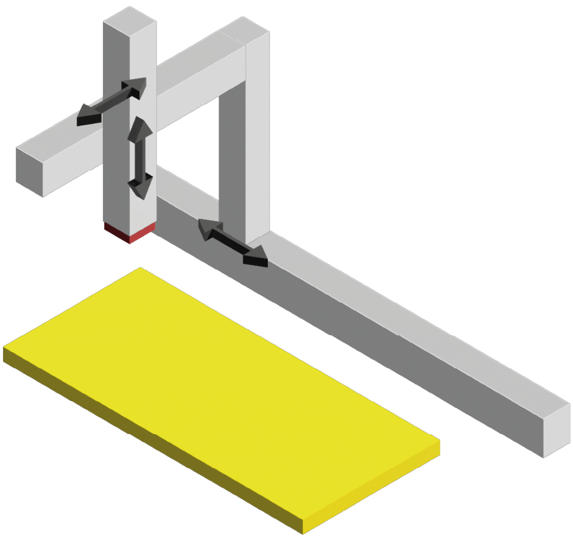


Figure D.1: Layout illustrating chosen subconcepts 1 to 5 of the low tech theme concept.

D.2 Concept 2 - Medium Tech

Table D.2: Medium Tech Concept

Subfunction	**Medium Tech**
1. Number of Welding Robots	2 units
2. External Axes	1 pc XYZ Pillar Gantry
3. In-Cell Buffer	1 unit
4. Loading of Wear Plates	Overhead Crane
5. Fixation of Wear Plates	Manual Tack Welding
6. Calibration of Nominal Positions	Laser Line Profiling
7. Seam Tracking	Laser
8. Wear Plate Design Changes	Offset Intermittent Walls
	Increase Base Angles
	Round Sharp Corners
	Flat Bar Redesign
9. Weld Torch Setup	2 Single & 1 Twin
10. Program Weld Location & Parameters	Import CAD Data
11. Plan & Optimize Weld Paths	Auto-Solve Deterministic

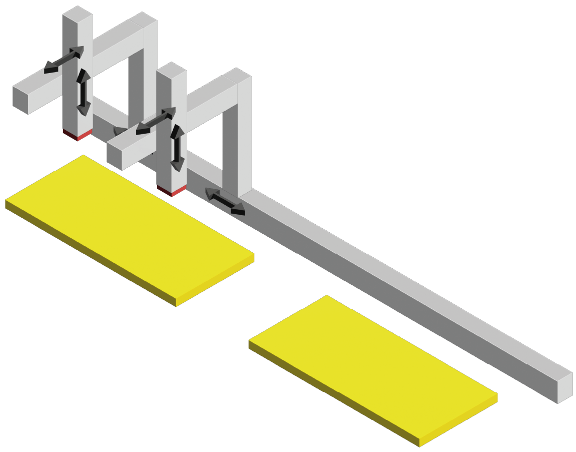


Figure D.2: Layout illustrating chosen subconcepts 1 to 5 of the medium tech theme concept.

D.3 Concept 3 - High Tech

Table D.3: High Tech Concept

Subfunction	High Tech
1. Number of Welding Robots	2 units
2. External Axes	1 pc XYZ Pillar Gantry (Rot Z) 1 pc XYZ Bridge Gantry
3. In-Cell Buffer	1 unit
4. Loading of Wear Plates	Robot with Gripper
5. Fixation of Wear Plates	Manual Tack Welding
6. Calibration of Nominal Positions	Laser Line Scan
7. Seam Tracking	Laser
8. Wear Plate Design Changes	Offset Intermittent Walls Modify Welding Angles Reduce Wear Plate Size Round Sharp Corners Flat Bar Redesign
9. Weld Torch Setup	2 Single & 1 Twin
10. Program Weld Location & Parameters	Import CAD Data
11. Plan & Optimize Weld Paths	Auto-Solve Deterministic

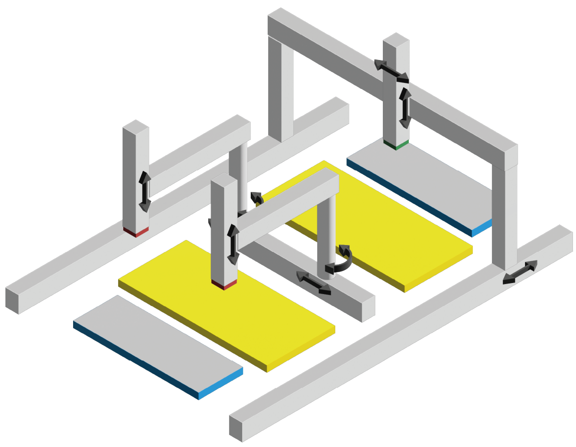
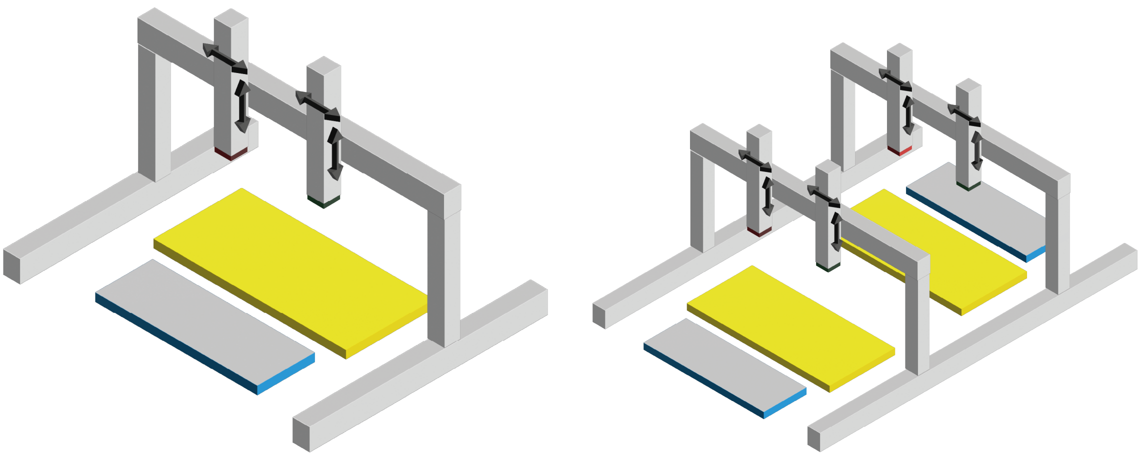


Figure D.3: Layout illustrating chosen subconcepts 1 to 5 of the high tech theme concept.

D.4 Concept 4 - Innovative

Table D.4: Innovative Concept

Subfunction	Innovative
1. Number of Welding Robots	1 unit
2. External Axes	1pc XYZ Bridge Gantry
3. In-Cell Buffer	None
4. Loading of Wear Plates	Robot with Gripper
5. Fixation of Wear Plates	Robot Tack Welding
	Robot With Gripper
6. Calibration of Nominal Positions	Laser Scanning
7. Seam Tracking	Digital Twin
8. Wear Plate Design Changes	Offset Intermittent Walls
	Increase Base Angles
	Reduce Wear Plate Size
	Round Sharp Corners
	Flat Bar Redesign
9. Weld Torch Setup	2 Single & 1 Twin
10. Program Weld Location & Parameters	Auto-Detect
11. Plan & Optimize Weld Paths	Reinforcement Learning



(a) Single Cell **(b)** Double Cell

Figure D.4: Layouts illustrating chosen subconcepts 1 to 5 of the innovative theme concept.

E

Workpiece Positioner Morphological Matrix

Table E.1: Morphological matrix for the workpiece positioner concept generation.

Morphological Matrix				
Subfunction	**Solutions**			
1. Loading	Rail	Overhead crane	AGV	Motor driven cart
2. Interface design	Head/Tailstock	Cradle	Table,shortside	Table, bottom middle
	Multiple side attachment points	Table with track	Motion platform	Hamster wheel
	Rotator	C-positioner	Skyhook	Rotating lift
	Grappling arms, longside	Grappling arms, shortside	Swing	Head/Tailstock longside
3. Suspension	Bolted adapter	Loose resting pin	Locking pin	Magnet
	Hooks	Gripper	Unique product frame	
4. Roll	Motion platform	Worm drive	Rotating hydraulic cylinders	Electric motors
	Rotating pneumatic cylinders	Turntable	Tracks	Lifting differance
5. Pitch	Motion platform	Lifting differance	Positioning table	
6. Yaw	Turntable	Circular tracks	Electric motor	
7. Surge	Motion platform	Tracks	Wheels	Hydraulic cylinders
	Pneumatic cylinders	Extendable suspension	AGV	
8. Heave	Motion platform	Lifting motor	Crane	Hydraulic cylinders
	Pneumatic cylinders	Ball screw	Scissor	Tracks
9. Sway	Motion platform	Wheels	Tracks	Hydraulic cylinders
	Pneumatic cylinders	Ball screw	AGV	
10. Unloading	Rail	Travers	AGV	Motor driven cart

F

Robotics, Advantages & Disadvantages

Table F.1: Number of welding robots, relative advantages and disadvantages.

	Advantages	**Disadvantages**
1 robot	- Smaller investment cost - Can handle the required capacity - Easier to program and implement	- Longer cycle times, can handle lower volumes - Not very redundant system
2 robots	- Reduced cycle times - More future-proof, can handle higher volumes - More redundant system	- Larger investment cost - Larger programming effort
3 robots	- Reduced cycle times - More future-proof, can handle much higher volumes - More redundant system	- Much larger investment cost - Much larger programming effort

Table F.2: External axes, relative advantages and disadvantages.

	Advantages	Disadvantages
2-Side YZ Gantry	- High robustness - Limited risk of robot collision and blocking - Better robot utilization balancing possible	- Only one robot can reach some of the welding - Very large construction, not cost-effective - Will obstruct loading/unloading - Large footprint
2-Side YZ Pillar Gantry	- Compact construction, more cost-effective - Limited risk of robot collision and blocking - Better robot utilization balancing possible - Medium footprint	- Only one robot can reach some of the welding - Will obstruct loading/unloading - Large construction, not cost-effective
XYZ Gantry	- Limited obstruction when loading/unloading - High robustness, longer X reach - Medium footprint - All robots can reach all welds	- Large construction, less cost-effective - Risk of robot collision and blocking with >1 robots - Higher ceiling required due to translating Z
XYZ Pillar Gantry	- All robots can reach all welds - Limited obstruction when loading/unloading - Compact construction, more cost-effective - Small footprint	- Medium robustness, not as long X reach - Risk of robot collision and blocking with >1 robots - Higher ceiling required due to translating Z
XYZ Pillar Gantry 2	- All robots can reach all welds - Limited obstruction when loading/unloading - Compact construction, more cost-effective	- Medium robustness, not as long X reach - Risk of robot collision and blocking with >1 robots - More space required behind due to X beam telescoping - Large footprint (due to point above)
2-Side XYZ Pillar Gantry 3	- No offset in Z required - Limited risk of robot blocking - Better robot utlization balancing possible - Not as high ceiling height required	- Only one robot can reach some of the welding - Large construction, not cost-effective - Can obstruct loading/unloading - Very large footprint - Risk of robot collision and blocking
XYZ Pillar Gantry Rot Z	- All robots can reach all welds - No obstruction when loading/unloading - Compact construction, more cost-effective - Small footprint - Working area on both sides of pillar gantry track	- Medium robustness, not as long X reach - Risk of robot collision and blocking with >1 robots - Righer ceiling required due to Z beam telescoping
XYZ Overhead Gantry	- Very high robustness, longer X reach - Small/Medium footprint - Allows for another in-cell buffer setup	- Large construction, not cost-effective - Can obstruct loading/unloading - Large footprint - Risk of robot collision and blocking

Table F.3: In-cell buffer, relative advantages and disadvantages.

	Advantages	Disadvantages
None	- More flexible cell footprint	- Handling losses - Lower utilization and productivity
1 unit	- Increased utilization and productivity - Reduced handling losses	- Slightly larger investment
2 units	- Increased utilization and productivity - Reduced handling losses - Can be balanced with reduced tacking times	- Slightly larger investment

Table F.4: Loading of wear plates, relative advantages and disadvantages.

	Advantages	**Disadvantages**
Overhead Crane Magnet	- Larger work area, not only dedicated for cell - Cost-effective - Simple implementation - Can be used for moving other products in facility	- Can be occupied, lower availability
Handling Robot	- Increased safety and work environment - Increased productivity	- Large investment cost - May not be fully utilized when producing other products - Can block when not assemblying wear plates - Complex solution
Prepared Kit in Fixture/Jigg	- Increased productivity, reduced tacking time	- Large investment cost - Many different fixtures probably needed - May not be fully utilized when producing other products - Complex solution - Larger cell footprint required
Gantry Crane Magnet	- Cost-effective - Simple implementation - Dedicated to cell, higher availability	- Smaller work area, only dedicated for cell

Table F.5: Fixation of wear plates, relative advantages and disadvantages.

	Advantages	**Disadvantages**
Manual Tack Welding	- Simple and cost-effective - More flexible - More robust	- Less safe and worse work environment
Robot Tack Welding	- Improved safety and work enviroment	- Very complex and expensive - Less robust

Table F.6: Calibration of nominal positions, relative advantages and disadvantages.

	Advantages	Disadvantages
Electrode Touch-Sense	- Low complexity and cost - Integrated in robot controllers, power supplies, and offline softwares - Better reachability than gas nozzle	- Time consuming - Not very robust for larger deviations/variations - Less accurate than gas nozzle - Require low variation in electrode stick-out - Must cut electrode before each search cycle
Gas Nozzle Touch-Sense	- Low complexity and cost - Integrated in robot controllers and power supplies - Better accuracy than electrode	- Time consuming - Not very robust for larger deviations/variations - Worse reachability than electrode
Laser Proximity	- Can be faster than touch-sense	- Laser sensor can block some welding positions - Reflective surfaces and welding smoke can distort data - Perpendicular measurements required, prone for large robot movements
Laser Point Profiling	- Only one robot motion required	- Laser sensor can block some welding positions - Reflective surfaces and welding smoke can distort data
Laser Line Profiling	- Faster than laser proximity and laser point profiling	- Laser sensor can block some welding positions - Reflective surfaces and welding smoke can distort data
Laser Line Sweep Scans	- More data supporting a flexible application	- Takes time to scan large objects - Can be expensive depending on setup - Laser sensor can block some welding positions - With several sensors, dedicated robot or tool change required
Structured Light	- More data supporting a flexible application	- Takes time to scan large objects - Expensive and very complex - Tool change or dedidated robot required - Sensitive to environment and lightning conditions
Laser Scanning	- More data supporting a flexible application - More accurate than structured light - Scan time shorter than structured light - No dedicated robot or tool change required	- Very expensive and complex - Some areas might not be reached from a single position

Table F.7: Seam tracking, relative advantages and disadvantages.

	Advantages	Disadvantages
Through-Arc	- Cheap and simple	
Laser	- High welding speeds possible - Robust technology - High resolution and accuracy	- Welding smoke can cause issues
Vision Camera	- Can be combined with quality assessments	- Welding smoke can cause issues
Digital Twin	- Robust, can handle larger variations - High welding speeds possible	- Expensive and complex - Point cloud of joint required

Table F.8: Wear plate design changes, relative advantages and disadvantages.

	Advantages	**Disadvantages**
Enlarge Slots	- Slightly more flexible wear plates	- Large redesign effort required - Higher internal stress levels induced - Larger safety volume required for automatic loading - Cycle times increased
Offset All Walls	- Improves reachability for tight joints	- Wear plate size significantly reduced - Large redesign effort
Offset Intermittent Walls	- Improves reachability for tight joints - Wear plate size not significantly reduced	- Large redesign effort
Modify Welding Angles	- No wear plate dimension reduction - Improves reachability for tight joints	- Stricter quality controls required
Reduce Wear Plate Sizes	- Higher degree of automation possible	- Large redesign effort - Affects the protection rate
Round Sharp Corners	- Improved productivity	- Medium redesign effort
Self-Locating Parts	- Improved productivity	- Large redesign effort
Flat Bar Redesign	- Improved productivity	- Small redesign effort

Table F.9: Welding torch setup, relative advantages and disadvantages.

	Advantages	**Disadvantages**
1 Single	- Cheaper and simpler - No torch neck change station required - Good reachability	- Limited welding speed - Poor flexibility
2 Single	- Excellent reachability	- Limited welding speeds - Poor flexibility
1 Twin	- Higher welding speed possible - Cheaper and simpler - No torch neck change station required	- Poor reachability - Poor flexibility
1 Single & 1 Twin	- Higher welding speed possible - Good reachability - Good flexibility	- Slightly more expensive - Torch neck change station required
2 Single & 1 Twin	- Higher welding speed possible - Excellent reachability - Great flexibility	- Slightly more expensive - Torch neck change station required

Table F.10: Program weld locations and parameters, relative advantages and disadvantages.

	Advantages	**Disadvantages**
Manual	- Simple and no investment cost	- Time consuming
Import CAD Data	- Reduced time spent on programming - Requires limited programming experience	- Requires advanced CAD-data - Investment cost and integration effort
Auto-Detect	- Reduced time spent on programming - Requires limited programming experience	- Not very robust - Still require input from programmer - Investment cost and integration effort

Table F.11: Plan and optimize weld paths, relative advantages and disadvantages.

	Advantages	**Disadvantages**
Manual	- Simple and no investment cost	- Time consuming
Import CAD Data	- Reduced time spent on programming - Requires limited programming experience	- Requires advanced CAD-data - Investment cost and integration effort
Auto-Detect	- Reduced time spent on programming - Requires limited programming experience	- Not very robust - Still require input from programmer - Investment cost and integration effort

G

Robotics Evaluation Matrix

Table G.1: Evaluation matrix results for the robotics.

	WEIGHT	Low Tech		Medium Tech		High Tech		Innovative	
Criteria		**Rating**	**Weighted Score**	**Rating**	**Weighted Score**	**Rating**	**Weighted Score**	**Rating**	**Weighted Score**
Cost	5	**5**	*25*	**4**	*20*	**2**	*10*	**1**	*5*
Flexibility	2	**1**	*2*	**2**	*4*	**3**	*6*	**5**	*10*
Future-Proof	1	**1**	*1*	**3**	*3*	**3**	*3*	**5**	*5*
Productivity	4	**2**	*8*	**5**	*20*	**5**	*20*	**2**	*8*
Programming Complexity	4	**1**	*4*	**4**	*16*	**4**	*16*	**5**	*20*
Ergonomics & Work Environment	5	**3**	*15*	**3**	*15*	**3**	*15*	**5**	*25*
Maintenance/Redundancy	2	**1**	*2*	**5**	*10*	**5**	*10*	**5**	*10*
Implementation Complexity	3	**5**	*15*	**3**	*9*	**2**	*6*	**1**	*3*
TOTAL			**72**		**97**		**86**		**86**

H

Elimination Matrix

Table H.1: Elimination matrix results.

Elimination Matrix								
Concept	**Solves main problem**	**Fulfills all demands**	**Realisable**	**Reasonable cost**	**Safe**	**Enough information**	**Comment**	**Decision**
Concept 1	+	+	+	+	+	+		
Concept 2	+	+	-				Grippers not strong enough	
Concept 3	+	+	+	+	+	+		
Concept 4	+	+	+	+	+	+	Could block wear plates	
Concept 5	-						No tilt	
Concept 6	+	-					Only tilt in one direction	
Concept 7	-						No rotation	
Concept 8	+	+	+	+	+	+		
Concept 9	+	+	+	+	+	+	Could block weld seams	
Concept 10	-						No rotation	
Concept 11	-						No rotation	
Concept 12	+	+	+	+	+	+	Could block wear plates	
Concept 13	+	+	+	+	+	+		
Concept 14	+	+	+	+	+	+		
Concept 15	+	+	+	+	+	+	Could block wear plates	
Concept 16	+	+	+	+	+	+		
Concept 17	+	+	+	+	+	+		
Concept 18	+	+	+	+	+	+	Could block weld seams	
Concept 19	-						No rotation	
Concept 20	+	-					Only tilt in one direction	
Concept 21	+	-					Not full rotation	
Concept 22	+	+	+	-			Price?	
Concept 23	+	-					Not product flexible	
Concept 24	+	+	+	+	+	+		
Concept 25	+	+	+	+	+	+		
Concept 26	-						No rotation	
Concept 27	+	-					Only tilt in one direction	
Concept 28	-						No rotation	
Concept 29	+	+	+	+	+	+	Could block weld seams	
Concept 30	+	+	+	+	+	+	Could block wear plates	
Concept 31	-						Only tilt in one direction	
Concept 32	+	+	+	+	+	+		
Concept 33	+	-					Not full rotation	
Concept 34	+	+	+	+	+	+		
Concept 35	-						No rotation	
Concept 36	+	-					Not full rotation	
Concept 37	+	+	+	+	+	+		
Concept 38	+	+	+	+	+	+		
Concept 39	+	+	+	+	+	+		
Concept 40	+	+	+	+	+	+		

I

Pugh Matrix 1

Table I.1: Pugh matrix 1 results, part one.

Pugh Matrix 1						
Criteria	**Concepts**					
	(Reference) Concept 4	**Concept 1**	**Concept 3**	**Concept 8**	**Concept 9**	**Concept 12**
Interface adaptability to future products	0	0	0	+	+	0
Blocking of weld seams	0	+	+	+	-	0
Block loading of wear plates	0	+	+	+	-	0
Time (Loading)	0	0	0	+	-	0
Time (Unloading)	0	0	0	+	-	0
No need for overhead crane	0	+	+	+	0	+
Cost effectiveness	0	+	+	-	-	0
Space efficiency	0	+	+	0	-	+
Pitch (+/-30°)	0	0	0	0	0	0
Repeatability and Accuracy (+/- 0,5 mm)	0	-	-	-	0	0
Programming complexity	0	0	0	0	0	0
Robustness	0	0	0	-	0	0
Movement efficiency	0	0	0	0	0	+
Lifespan	0	+	+	-	-	0
In-house experience	0	0	-	-	-	0
Time to learn	0	0	-	0	0	-
Adaptability for future facility changes	0	-	-	+	2	-
Σ +	0	6	6	7	2	3
Σ -	0	2	4	5	8	2
Σ 0	16	9	7	5	7	12
Total	0	4	2	2	-6	1
Further Development	No	Yes	Yes	Yes	No	No

Table I.2: Pugh matrix 1 results, part two.

Pugh Matrix 1							
Concept 13	**Concept 14**	**Concept 15**	**Concept 16**	**Concept 17**	**Concept 18**	**Concept 24**	**Concept 25**
0	0	0	+	+	+	+	+
+	+	0	-	-	-	-	+
+	+	0	+	+	+	+	+
0	0	0	0	+	+	+	+
0	0	0	0	+	+	+	+
+	+	+	+	0	-	-	+
+	+	+	+	-	0	0	-
+	0	+	+	-	0	0	0
0	0	0	0	-	0	0	0
-	0	0	0	-	-	-	-
0	0	0	0	-	0	0	0
0	0	0	-	-	0	0	-
0	0	+	0	-	0	0	0
+	0	0	0	+	+	+	-
0	0	0	0	-	-	-	-
0	0	0	0	-	-	0	0
-	-	-	-	0	0	0	+
6	4	4	5	6	5	5	7
2	1	1	3	10	4	4	5
9	12	12	9	2	7	8	5
4	3	3	2	-4	1	1	2
Yes	Yes	Yes	Yes	No	No	No	Yes

Table I.3: Pugh matrix 1 results, part three.

Pugh Matrix 1							
Concept 29	**Concept 30**	**Concept 32**	**Concept 34**	**Concept 37**	**Concept 38**	**Concept 39**	**Concept 40**
+	0	+	0	0	0	0	+
-	0	+	-	+	+	+	+
-	0	+	-	+	+	+	+
-	0	+	0	0	0	0	+
-	0	+	0	0	0	0	+
-	+	+	+	+	+	+	+
0	0	-	+	-	0	+	-
-	0	0	+	+	0	+	0
0	0	0	-	0	0	0	0
-	-	-	0	-	-	+	0
0	0	0	0	0	0	0	0
0	0	-	-	0	0	0	-
0	0	0	0	+	0	0	0
0	0	0	-	0	0	-	0
-	0	-	-	0	0	0	-
0	0	0	-	0	0	0	0
0	+	+	+	+	+	+	+
1	1	7	4	6	4	7	7
7	1	4	7	2	1	1	3
8	14	6	6	9	12	9	7
-6	0	3	-3	4	3	6	4
No	No	Yes	No	Yes	Yes	Yes	Yes

J

Pugh Matrix 2

Table J.1: Pugh matrix 2 results, part one.

Pugh Matrix 2						
Criteria	**Concepts**					
	(Reference) Concept 14	**Concept 1**	**Concept 3**	**Concept 8**	**Concept 9**	**Concept 12**
Interface adaptability to future products	0	0	0	+	+	0
Blocking of weld seams	0	0	0	0	-	-
Block loading of wear plates	0	0	0	0	-	-
Time (Loading)	0	0	0	+	-	0
Time (Unloading)	0	0	0	+	-	0
No need for overhead crane	0	0	0	0	0	0
Cost effectiveness	0	+	+	-	-	+
Space efficiency	0	+	+	0	-	+
Pitch (+/-30° from bottom plate)	0	0	0	0	0	0
Repeatability and Accuracy (+/- 0,5 mm)	0	-	-	-	0	0
Programming complexity	0	0	0	0	0	0
Robustness	0	0	0	-	0	0
Movement efficiency	0	0	0	0	0	+
Lifespan	0	+	+	0	-	0
In-house experience	0	0	-	-	-	0
Time to learn	0	0	-	0	0	-
Adaptability for future facility changes	0	-	-	+	+	-
Σ +	0	3	3	4	2	3
Σ -	0	2	4	4	8	4
Σ 0	16	12	10	9	6	10
Total	0	1	-1	0	-6	-1
Further Development	Yes	Yes	No	Yes	No	No

Table J.2: Pugh matrix 2 results, part two.

Pugh Matrix 2							
Concept 13	**Concept 4**	**Concept 15**	**Concept 16**	**Concept 17**	**Concept 18**	**Concept 24**	**Concept 25**
0	0	0	0	+	+	+	+
0	-	-	-	-	-	-	0
0	-	-	0	0	0	0	0
0	0	0	0	+	+	+	+
0	0	0	0	+	+	+	+
0	0	0	0	-	-	-	0
+	-	+	+	-	-	-	-
+	0	+	+	-	0	0	0
0	0	0	0	-	0	0	0
-	0	0	0	-	-	-	-
0	0	0	0	-	0	0	0
0	0	0	-	-	0	0	-
0	0	+	0	-	0	0	0
+	-	0	0	-	-	0	0
0	0	0	0	-	-	-	-
0	0	0	0	-	-	0	0
-	0	-	-	0	0	0	+
3	0	3	2	4	3	3	4
2	4	3	3	10	7	5	4
12	13	9	12	2	7	9	9
1	-4	0	-1	-6	-4	-2	0
Yes	No	Yes	No	No	No	No	Yes

Table J.3: Pugh matrix 2 results, part three.

Pugh Matrix 2							
Concept 29	**Concept 30**	**Concept 32**	**Concept 33**	**Concept 37**	**Concept 38**	**Concept 39**	**Concept 40**
+	0	+	0	0	0	0	+
-	0	0	-	0	0	0	0
-	-	0	-	0	0	0	0
-	0	+	0	0	0	0	+
-	0	+	0	0	0	0	+
-	0	0	0	0	0	0	0
-	-	-	-	0	-	0	-
-	0	0	+	+	0	+	0
0	0	0	-	0	0	0	0
-	-	-	0	-	-	0	-
0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0
0	0	0	0	+	0	0	0
-	0	0	-	0	0	-	0
-	0	-	-	0	0	0	-
0	0	0	-	0	0	0	0
0	+	+	+	+	+		+
1	1	4	2	3	1	1	4
10	3	3	7	1	2	1	3
6	13	10	8	13	14	14	10
-4	-2	1	-5	2	-1	0	1
No	No	Yes	No	Yes	No	Yes	Yes

K

Kesselring

Table K.1: Kesselring matrix results, part one.

Kesselring Matrix									
Concepts →		**Ideal**		**Concept 1**		**Concept 8**		**Concept 13**	
Criteria	w	v	t	v	t	v	t	v	t
Interface adaptability to future products	5	5	25	2	10	5	25	2	10
Blocking of weld seams	5	5	25	5	25	5	25	5	25
Block loading of wear plates	5	5	25	5	25	5	25	5	25
Time (Loading)	3	5	15	1	3	5	15	1	3
Time (Unloading)	3	5	15	1	3	5	15	1	3
No need for overhead crane	1	5	5	5	5	5	5	5	5
Cost-effectiveness	4	5	20	5	20	1	4	5	20
Space efficiency	2	5	10	5	10	1	2	5	10
Pitch (+/-30°)	4	5	20	5	20	5	20	5	20
Repeatability and Accuracy	3	5	15	3	9	1	3	3	9
Programming complexity	2	5	10	5	10	3	6	5	10
Robustness	5	5	25	5	25	1	5	1	5
Movement efficiency	2	5	10	5	10	5	10	5	10
Lifespan	2	5	10	5	10	3	6	4	8
In-house experience	1	5	5	3	3	1	1	3	3
Time to learn	1	5	5	3	3	5	5	3	3
Adaptability for facility changes	5	5	25	1	5	5	25	1	5
T = ∑ ti		220		196		197		174	
T / Tmax				89%		90%		79%	
Ranking				5		4		9	

Table K.2: Kesselring matrix results, part two.

Kesselring Matrix													
Concept 15		**Concept 25**		**Concept 14**		**Concept 32**		**Concept 37**		**Concept 39**		**Concept 40**	
v	t	v	t	v	t	v	t	v	t	v	t	v	t
1	5	5	25	2	10	5	25	5	25	2	10	5	25
5	25	5	25	5	25	5	25	1	5	5	25	5	25
1	5	5	25	5	25	5	25	5	25	5	25	5	25
1	3	5	15	1	3	5	15	1	3	1	3	5	15
1	3	5	15	1	3	5	15	1	3	1	3	5	15
5	5	5	5	5	5	5	5	5	5	5	5	5	5
5	20	1	4	1	4	1	4	2	8	2	8	1	4
5	10	1	2	1	2	5	10	1	2	5	10	1	2
5	20	5	20	5	20	5	20	5	20	5	20	5	20
5	15	1	3	5	15	1	3	3	9	5	15	1	3
5	10	1	2	5	10	5	10	5	10	5	10	5	10
5	25	1	5	5	25	1	5	5	25	5	25	1	5
5	10	1	2	5	10	5	10	5	10	5	10	5	10
3	6	3	6	3	6	3	6	3	6	3	6	3	6
5	5	1	1	3	3	1	1	3	3	3	3	1	1
3	3	1	1	3	3	5	5	3	3	3	3	5	5
1	5	5	25	1	5	5	25	5	25	5	25	5	25
175		181		174		209		187		206		201	
80%		82%		79%		95%		85%		94%		91%	
8		7		9		1		6		2		3	

L
Loading and Unloading Comparison

Table L.1: Relative advantages and disadvantages of rail, AGV or overhead crane for loading.

	Advantages	**Disadvantages**
Rail	- Cheap buying cost - Carries heavy weights - Long lifespan	- Expensive to remove or change - Limited lifting capabilities - Routes limited to rail - Laying rail throughout factory
AGV	- Flexible, can drive anywhere - Carries heavy weights - Easy to change routes - Quicker unloading and loading	- Limited lifting capabilities - High buying costs - Charging
Overhead crane	- Lifting capabilities - Long lifespan	- Reinforce roof and beams for 20 ton load - Not designed for longer transports

M

Production Concept, Dimensional Drawings

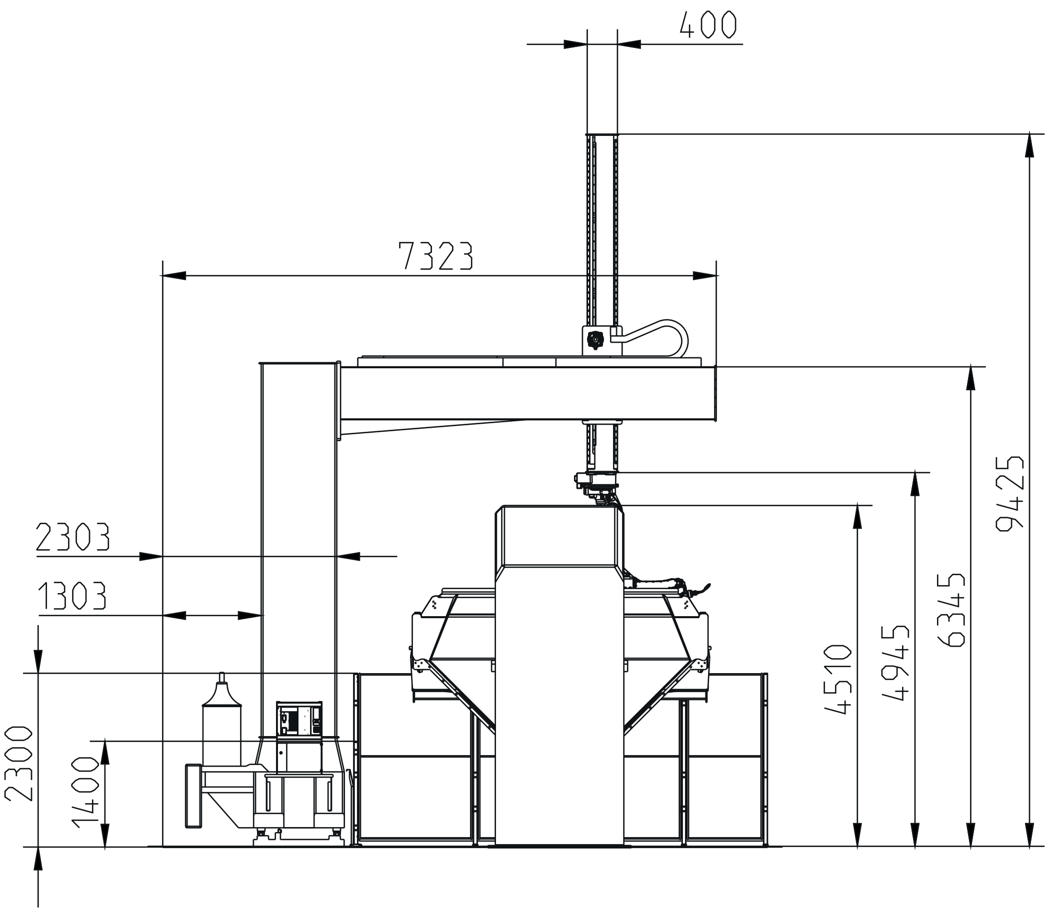


Figure M.1: Side view dimensional drawing, all dimensions in millimetres.

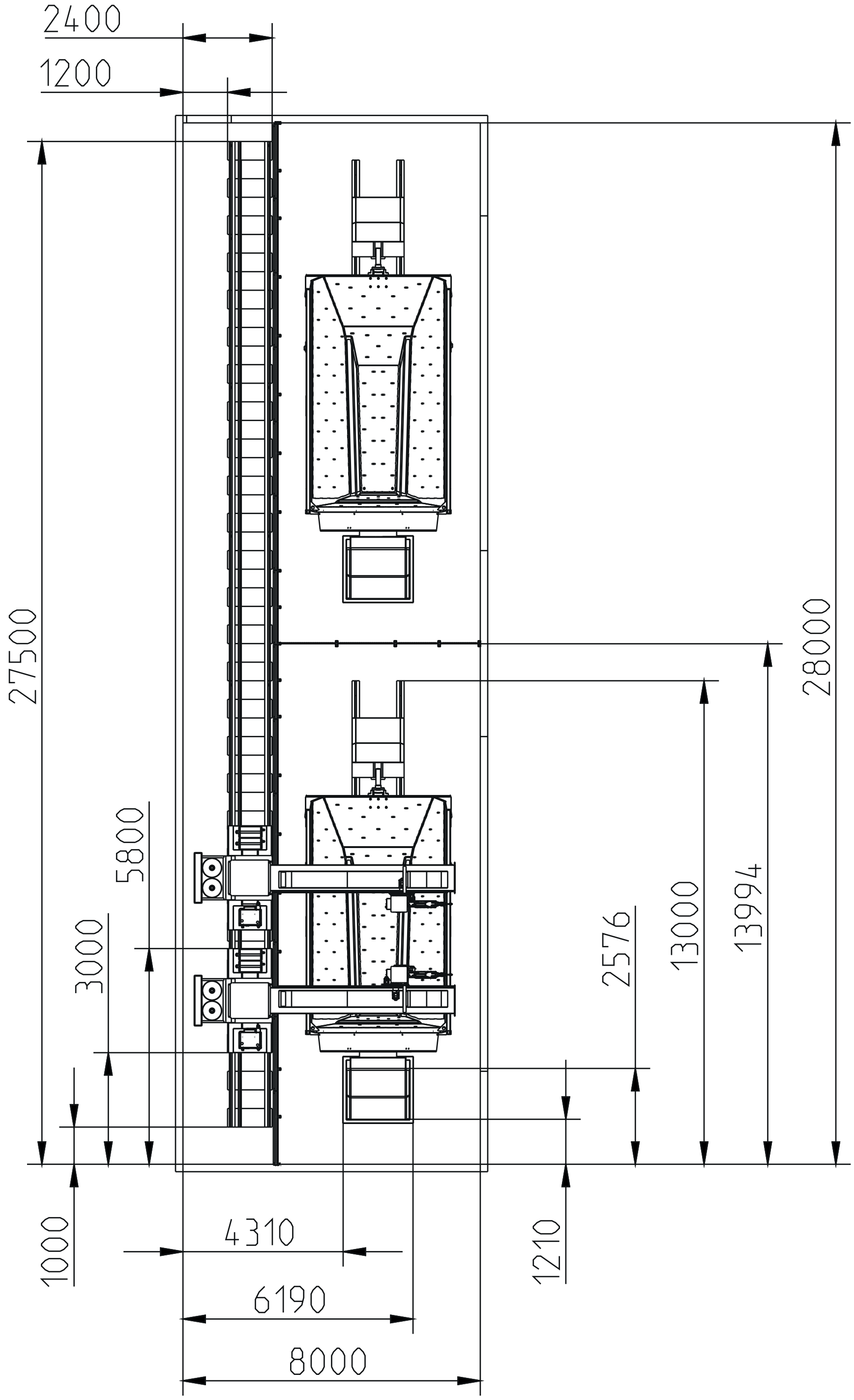


Figure M.2: Top view dimensional drawing, all dimensions in millimetres.

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